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Use of Traffic Displays for General Aviation Approach Spacing: A Human Factors Study

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16. Abstract

A flight experiment was conducted to assess human factors issues associated with pilot use of traffic displays for approach spacing. Sixteen multi-engine rated pilots participated. Eight flew approaches in a twin-engine Piper Aztec originating in Sanford, ME, and eight flew approaches in the same aircraft originating in Atlantic City, NJ. The spacing target was a Cessna 206. The traffic display was either a Garmin International MX-20™ (the "Basic" Cockpit Display of Traffic Information, or CDTI) or an MX-20™ modified with features to help the pilot monitor the closing rate, the range and ground speed of the traffic-to-follow, and ownship ground speed (Range Monitor). Two other Equipment conditions were Baseline and Autopilot. Pilots successfully used the displays to maintain the assigned spacing on visual and instrument approaches. The spacing deviations were significantly lower when using the displays during visual approaches than when attempting to maintain spacing without a traffic display. The mean spacing deviation during the IFR approaches was less than 0.10 NM for all three equipment conditions (Basic CDTI, Range Monitor, Autopilot), and these mean spacing deviations did not differ significantly. Range Monitor features appeared to particularly benefit the low-hour pilots. While the traffic display reduced visual reacquisition times, this effect was only found with pilots whose displays showed additional traffic (not only the traffic-to-follow). In general, however, the additional traffic was associated with less time between fixations on the display and higher workload. Subjects appeared to have had difficulty identifying an optimal display range that would simultaneously provide traffic awareness and spacing task performance. The traffic display necessarily requires visual attention and reduces the attention available for scanning the instrument panel and on visual approaches, the outside world. For this reason, even if pilots assume responsibility for spacing when they temporarily lose visual contact with the assigned traffic-to-follow, they should notify ATC of the loss of visual contact so that controllers can assume responsibility for separation from other aircraft.

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EXECUTIVE SUMMARY

A flight experiment was conducted to assess human factors issues associated with pilot use of traffic displays for approach spacing. Sixteen multi-engine rated pilots participated. Eight flew approaches in a twin-engine Piper Aztec originating in Sanford, ME, and eight flew approaches in the same aircraft originating in Atlantic City, NJ. The spacing target was a Cessna 206. The pilots were assigned a spacing interval that was the same as their current spacing during the downwind leg of the flight pattern. The traffic display was either a Garmin International MX-20™ (the "Basic" Cockpit Display of Traffic Information, or CDTI) or an MX-20™ modified with features to help the pilot monitor the closing rate, the range and ground speed of the traffic-to-follow, and ownship ground speed (Range Monitor). Two other Equipment conditions were Baseline and Autopilot. The Baseline protocol during the visual approaches consisted of using no traffic display. The Baseline protocol during the instrument approaches consisted of flying the approach without attempting to maintain a specific spacing interval. The Range Monitor was used with the autopilot coupled on some instrument approaches and with manual control on the visual approaches and some instrument approaches.

The position, identity, and ground speed of the Cessna were displayed for subject pilots via Automatic Dependent Surveillance – Broadcast (ADS-B). Traffic Information Service-Broadcast (TIS-B) transmitted aircraft position and identity for other aircraft within display range for the Atlantic City pilots only. The display of additional traffic was thus varied between groups of subjects. Pilots were divided into two groups having relatively high and low flight hours for purposes of analysis. Each pilot flew four visual approaches followed by four instrument approaches. The primary task, apart from flying the aircraft, was to maintain the assigned spacing. Pilots were asked to maintain at least the assigned spacing during the visual approaches and simply to maintain the assigned spacing during the instrument approaches. During each visual approach, the pilots were asked to look down for one minute to create a temporary loss of visual contact and afterwards to visually re-acquire the aircraft as soon as possible. The traffic-to-follow decelerated markedly on all approaches either prior to or following the outer marker. The loss of visual contact either overlapped or occurred separately from lead aircraft deceleration.

The dependent performance measures consisted of deviations from the assigned spacing interval on all approaches and localizer and glide slope deviations on the instrument approaches. The time taken to re-acquire the traffic-to-follow after the head-down interval had ended was obtained from videotape recording. Pilots wore a device to record their eye fixations and provide additional objective measurements. Three measures were derived from these records: the percent allocation of visual attention to the forward window, instrument panel, and traffic display; the dwell duration on these areas of interest; and the "look away duration" for each. For example, "head-down time" was defined as the look away duration for the window. Pilots orally provided subjective workload estimates on the six NASA-TLX workload dimensions following each approach. Questionnaires that focused on task performance, situational awareness, and usability were administered following each set of visual and instrument approaches.

Pilots successfully used the displays to maintain the assigned spacing on visual and instrument approaches. The spacing deviations were significantly lower when using the displays during visual approaches than when attempting to maintain spacing without a traffic display. The mean spacing deviation during the IFR approaches was less than 0.10 NM for all three equipment conditions (Basic CDTI, Range Monitor, Autopilot), and these mean spacing deviations did not differ significantly. Range Monitor features appeared to particularly benefit the low-hour pilots. While the traffic display reduced visual reacquisition times, this effect was only found with pilots whose displays showed additional traffic (not only the traffic-to-follow). In general, however, the additional traffic was associated with less time between fixations on the display and higher workload. Subjects appeared to have had difficulty identifying an optimal display range that would simultaneously provide traffic awareness and spacing task performance. The traffic display necessarily requires visual attention and reduces the attention available for scanning the instrument panel and on visual approaches, the outside world. For this reason, even if pilots assume responsibility for spacing when they temporarily lose visual contact with the assigned traffic-to-follow, they should notify ATC of the loss of visual contact so that controllers can assume responsibility for separation from other aircraft.

CONTENTS

USE OF TRAFFIC DISPLAYS FOR GENERAL AVIATION APPROACH SPACING: A HUMAN FACTORS STUDY

OBJECTIVE

The FAA Flight Standards Flight Technologies and Procedures Division (AFS-430) requested this study of pilot spacing performance and human factors related to air traffic display use. The objective was to assess the performance of appropriately rated pilots using a cockpit display of traffic information (CDTI) to aid in visually acquiring an air traffic control (ATC) designated spacing target aircraft and maintaining assigned spacing, or in identifying and maintaining the assigned spacing during instrument flight. Performance, pilot situation awareness, and the usability of the human interface to the CDTI were studied under visual and instrument flight conditions in Automatic Dependent Surveillance - Broadcast (ADS-B) and Traffic Information Service - Broadcast (TIS-B) environments. The CDTI to be used, while not intended specifically for these applications, is considered representative of avionics that would be utilized for such a purpose. In particular, the Garmin International MX-20™ or "Basic CDTI" is a less capable version of the Garmin AT-2000 that is currently undergoing evaluation in transport category aircraft by the Cargo Airlines Association and the FAA for use in pilot-performed spacing tasks. Garmin International provided additional features similar to those of the AT-2000 specifically for pilot spacing applications. The enhanced CDTI is called the Range Monitor. Since the current evaluation was intended to examine the use of the system by pilots who are capable of using it, sufficient training in its use was provided. Pilot ability to use all of the necessary functions was verified in exercises using simulated and familiarization flights.

BACKGROUND

The FAA Integrated Product Team (IPT) for Safe Flight 21 (AND-510) and the Cargo Airlines Association examined the use of the CDTI for enhanced visual approaches in an operational evaluation (FAA, 2000). Head-down time and workload were addressed on a pilot questionnaire. The flight crews indicated that they "perceived the workload for gauging the distance behind the aircraft ahead to be acceptable, although head-down time was reported to increase" (p.57). In this evaluation, pilots were given no specific spacing goals other than a recommendation to avoid closing to less than two miles.

In a second operational evaluation of approach spacing (FAA, 2001), the CDTI was used to reduce the variability in spacing between aircraft during visual approach to a full-stop landing. The flight crews attempted to achieve three- and five-mile intervals at the runway threshold. The CDTI included a target selection feature that displayed the range of the target, its ground speed, and the closure rate. In general, the two more mature prototypes tested received positive ratings for this application. The workload assessment found that mental effort was required to attain acceptable performance with this display. The crew instructions suggested that only the Pilot-Not-Flying (PNF) should monitor the CDTI and provide the Pilot Flying (PF) with appropriate guidance. However, this recommendation was followed by less than 60% of the flight crews, and roughly one-third of the PFs also monitored the display. The PFs reported competition between the head-up display of their primary flight information and the CDTI. PNFs reported additional workload and interruption of checklist activities to provide spacing information to the PF, and they missed ATC communications. Pilots interviewed reported that the task was difficult under the conditions imposed by the evaluation. Restrictions on lateral maneuvering reduced the ability of crews to use the CDTI to establish position to complete the spacing task. ATC expressed concern about potential overtakes. Forced to use speed alone, pilots expressed concern about the possible negative impact on a stabilized final approach. A communications analysis found operational concerns regarding speed and loss of visual contact in the long-spacing condition conducted under scattered/broken meteorological conditions. Nonetheless, overall, "changes due to CDTI in the flight crew's ability to maintain contact and spacing relative to targeted traffic were acceptable" (p. 120). Spacing performance was also successful. For final approach spacing with the short-spacing criteria (3 miles), 20 of the 23 aircraft pairs crossed the runway threshold within specified tolerance (+1, -.5NM). In the long spacing task, 24 of the 27 crossed the runway threshold within the specified tolerance. This spacing performance was achieved using speed adjustments, since lateral maneuvers to reduce spacing were prohibited.

The FAA Integrated Product Team for Safe Flight 21 and the MITRE Corporation have investigated a CDTI spacing application involving CDTI-Enhanced Flight

Rules (CEFR). In this application, the flight crew would be authorized to use the CDTI with the appropriate surveillance information (e.g., ADS-B) for the visual separation task, in lieu of visual Out-the-Window (OTW) contact with an aircraft initially during single stream visual approaches. Prior to using the CDTI for spacing, the flight crew must establish visual OTW contact with the traffic-to-follow (TTF) and then correlate that traffic with its displayed symbol on the CDTI. The CDTI may also be used to initially detect, monitor, and potentially re-acquire the TTF more effectively (RTCA, 2003).

In a series of four medium-fidelity cockpit simulations, Bone and collaborators (Bone, Domino, Helleberg, & Oswald, 2003; Bone, Helleberg, Domino, & Johnson, 2003a-c) asked airline pilots to perform CEFR. The simulations are referred to as CEFR 1, 2, 3, and 4. They were conducted under varying meteorological conditions and included loss of visual contact (from cloud layers) for varying lengths of time. The investigators collected questionnaire, workload, and objective spacing data to refine the application description and the associated procedures. Pilots strongly agreed that they would perform CEFR under any of the weather conditions simulated. Pilots also strongly agreed that they were more confident with the use of the CDTI as compared to using OTW visual cues for establishing appropriate spacing. Across all simulations, pilot responses were either that the CEFR procedure was "no more difficult than most precision approaches" or "more difficult than most precision approaches but the average line pilot can do it." No pilots said it was "very," "extremely," or "too" difficult. Pilots in CEFR simulations 3 and 4 agreed that overall workload while performing CEFR during visual approaches was acceptable and only slightly beyond that currently experienced with visual approaches. Pilots generally disagreed that the amount of head-down time had a negative impact on safety, but responses varied to this question. They strongly agreed that they had sufficient time to reacquire the traffic once they were below the clouds. This study extends what has been learned from airline pilot subjects in transport aircraft simulations to general aviation pilots performing a similar task under actual flight conditions.

METHOD

Participants

Sixteen current instrument-rated pilots with multi-engine ratings served as subjects. Their participation was solicited through an advertisement in The Atlantic Flyer magazine and through local flight schools. Eight who could participate in flights originating in Sanford, ME (KSFM) and eight who could participate in flights out of Atlantic City, NJ (KACY) were selected. Each was compensated $300.00. As dictated by appropriate Federal Air Regulations for pilots, they were required to not consume drugs or alcohol within an eight-hour period prior to participation. Pilots who wore glasses were excluded from participation to facilitate the use of eye movement recording (contact lenses were acceptable).

Equipment

Subject pilots flew a twin-engine Piper Aztec. The plane was equipped with a Horizontal Situation Indicator (HSI). The Garmin International MX-20™ multifunction traffic display or "Basic CDTI" and a "Range Monitor" CDTI, a Garmin International MX-20™ enhanced with Range Monitor features similar to the Garmin International AT-2000 were the avionics used in the study. The Range Monitor included the additional closing rate (CR) information (see Figure 1). The user interface included a six-inch diagonal liquid crystal display. The ground-based transmitter required for TIS-B traffic reception on the Basic CDTI and Range Monitor was operational only for the KACY pilots. The KSFM pilots' traffic reception was restricted to the TTF that broadcast ADS-B.

Pilot eye point of regard data were recorded automatically using a low-level infrared oculometer (ISCAN Model RK-726-BMP standalone eye tracking system and supporting software). The eight-ounce oculometer was mounted on a padded cloth headband. The positions of the Aztec and the TTF (a Cessna 206) were automatically recorded at 60 Hz. The experimenter in the Aztec could communicate with the subject pilot over the Aztec intercom or over a separate radio channel with the pilot of the Cessna without the subject hearing. A laptop computer automatically recorded glide slope and localizer data. The aircraft intercom channel was recorded during flight to allow for post-flight reduction of visual acquisition times.

Design and Procedure

The partially counterbalanced experimental design is shown in Tables 1 and 2. The spacing task was not performed during the Instrument Flight Rules (IFR) Baseline conditions. Rather, these approaches were flown solely to provide baseline data on flight technical error. The CDTI that the KSFM subjects used only showed the TTF, whereas the CDTI that the KACY subjects used in addition showed all traffic equipped with operating transponders that were within the selected CDTI range. The number of additional aircraft was estimated under the assumption that all TIS-B targets within a horizontal range of two miles and a vertical range of 2000 ft were displayed. Accordingly, the number displayed simultaneously

Figure 1. Range Monitor: Garmin International's MX-20™ user interface enhanced.

ranged from zero to five with a mean of 1.08 planes. The mean number of additional aircraft displayed during an approach for any subject ranged from .58 to 1.84.

The experiment's purpose and procedures were explained to each subject pilot including the use of eye movement recording equipment. The pilots wore the functioning oculometer prior to signing a voluntary consent form. After a pilot signed the consent form, he or she was trained on the use of the Basic CDTI and Range Monitor. Training ended when the pilot successfully completed a worksheet consisting of all CDTI functions and demonstrated its use during a practice approach.

Subjects flew a series of approaches in the Aztec under the conditions described in Table 1. During each CDTI approach, the pilot used the CDTI to respond to pseudo ATC instructions given by the experimenter. The experimenter asked the pilot to visually acquire and follow the participating lead aircraft (i.e., the TTF) at an assigned spacing interval on a low approach to the test airport. The assigned spacing maintained the current distance. During the Visual Flight Rules (VFR) approaches, the pilot was instructed to roll out on final with at least the designated number of miles spacing. Baseline VFR approaches consisted of attempting to maintain at least the assigned spacing without a traffic display. Under these circumstances, the pilots could only guess at their actual distance, and the distance that they maintained is perhaps best regarded as the spacing that they achieve when ATC instructs them to maintain visual separation. For the IFR approaches, the instruction was to maintain the specified spacing. Baseline IFR approaches consisted of flying an ILS approach without a CDTI and without the spacing task. At a point during each VFR approach the pilot was asked to look down to produce a loss of visual contact with the TTF. The experimenter asked the pilot to look up after one minute and re-acquire the TTF. Baseline VFR approaches were flown with and without the loss of visual contact. The TTF decelerated markedly during either the downwind leg or final approach. The deceleration either overlapped or occurred separately from the instructed loss of visual contact. At the missed approach point, the safety pilot took control of the aircraft. The start and end times of pilot spacing performance were recorded to isolate the period of interest for data reduction. The experimenter then verbally obtained pilot ratings on the six NASA TLX workload scales. The VFR approaches were flown during the morning, followed by landing and completion of the VFR questionnaire. After a break, the pilot flew the IFR approaches and completed the IFR questionnaire.

Dependent Measures

The following metrics were used in this study:

- Spacing performance. Comparisons with baseline spacing performance were only made during VFR spacing task performance.
- Flight technical error (FTE). FTE data were collected during all IFR approaches, including baseline approaches conducted without spacing task performance. They consisted of localizer and glide slope deviations.
- Visual reacquisition time. The time to visually reacquire TTF following the one-minute head-down interval was measured off line from videotape recordings.
- Eye data. Visual fixations were classified by area of interest: on the traffic display, forward window (for VFR approaches only), instrument panel, other flight deck areas, and undeterminable locations. Only those that occurred during the spacing task performance (or equivalent for the IFR baseline approaches) were analyzed. Those obtained on VFR approaches during the loss of visual contact, and reacquisition of the traffic-to-follow, were excluded from analysis.

The following dependent measures were derived from the eye data:

◊ Percentage allocation of visual attention to Basic CDTI, Range Monitor, and Baseline (no traffic display) on VFR approaches, and to Basic CDTI, Range Monitor (without autopilot), Range Monitor (with autopilot), and Baseline (without spacing) on IFR approaches.

◊ Dwell time on the instrument panel, traffic display, and forward window (VFR approaches only). Dwell time consisted of the time that the visual point of regard remained in the area of interest.

◊ Look-away duration for the instrument panel, traffic display, and forward window (VFR approaches only). Look-away duration consisted of the time between fixations on the area of interest. Head-down time was defined as the look away duration for the forward window.

- NASA-TLX (National Aeronautics and Space Administration -Task Load Index). Use of this measure required the in-flight experimenter to read the list of workload dimensions over the aircraft intercom and record the pilot's responses that were provided on a scale of zero (low workload) to 100 (high workload). The practicality, validity, and sensitivity of such scales have been demonstrated previously with subjects operating vehicles in the presence of additional brief "loading" tasks that artificially increased operator workload over that created by the primary (driving) task (Verwey & Veltman, 1996). The NASA-TLX workload dimensions are:

◊ Mental demand
◊ Physical demand
◊ Temporal demand (time pressure)
◊ Own performance
◊ Effort
◊ Frustration

- Questionnaires were administered upon landing after the VFR approaches and again after the IFR approaches. The VFR and IFR questionnaires reflected differences between the two spacing tasks. They used the same five-point Likert-type scale.

Hypotheses

In general, the experiment tested hypotheses regarding airspace efficiencies and the safety of using a traffic display for VFR and IFR approach spacing applications, where the VFR spacing application involves a temporary loss of visual contact with the TTF. An ancillary hypothesis was that the display of the TTF plus other nearby traffic would create an additional traffic awareness task, and hence it would contribute to higher workload. These general hypotheses were evaluated in terms of the following more specific hypotheses that pertained to the various metrics employed in the experiment:

- **Spacing Performance.** General aviation pilots using the Basic or Range Monitor CDTI will perform significantly more precise VFR approach spacing than they perform without a traffic display.
- **Flight Technical Error.** Flight technical error will significantly increase when the pilots use the Basic CDTI for IFR approach spacing.
- **Visual Reacquisition.** When using a traffic display pilots will reacquire the TTF more rapidly than when they are not using a traffic display.
- **Eye Movements.** Incorporation of the traffic display into the pilots' scan patterns will substantially reduce the allocation of visual attention to the forward window and instrument panel. Pilots will exhibit significantly longer dwells on the window on Baseline VFR approaches than on those flown with a traffic display. If traffic awareness is performed as a separate task, those pilots who use a CDTI that only shows the TTF will look away from the CDTI for significantly more time than those whose displays show other traffic.
- **Subjective Workload.** Basic CDTI approaches will result in significantly higher workload than the Range Monitor approaches, especially on the mental demand dimension. The display of other nearby traffic

will significantly increase pilot workload, suggesting that the use of a CDTI for traffic awareness is an additional task.

RESULTS

The variables analyzed for VFR approaches included Equipment, Hood, Flight Hours, Approach, and Subject. Equipment levels included Baseline, Basic CDTI, and Range Monitor (without Autopilot coupled). “Hood” refers to the initially planned procedure of using an instrument flight-training hood to ensure a loss of visual contact. This procedure was changed to a verbal request for the pilot to look down because a discrete event was needed for measurement of the start time for re-acquiring the traffic-to-follow. Hood consisted of three levels: “Separate” loss of visual contact and lead aircraft deceleration, “Overlapping” loss of visual contact and lead aircraft deceleration, and “No” loss of visual contact. Two Flight Hour groups were formed on the basis of a median split. The median number of total flight hours was 2,290 hours, with a range of 270 hours to 6,000 hours. The mean was 3,600.75 hours for the resulting High flight-hour group and 978.75 hours for the Low flight-hour group. The first four approaches were VFR. The variables analyzed for IFR approaches included Equipment (Baseline, Basic CDTI, Range Monitor without Autopilot, and Range Monitor with Autopilot coupled), Slowdown (lead aircraft deceleration “Prior” to outer marker or “Following” outer marker), Flight Hours, and Approach (5, 6, 7, or 8). For measures such as spacing distance that were not obtained during the IFR baseline approaches, only three levels of Approach were included in the analysis, nominally regarded as 5, 6, and 7, although the “missing” baseline approach data could have occurred during any of the IFR approaches due to counterbalancing.

The analysis of the VFR approach data included Hood as a between-subjects variable. The analysis of the IFR data included Slowdown as between-subjects. Flight Hours and Traffic were analyzed as between-subjects variables in both the VFR and IFR datasets. Equipment and Approach were analyzed as within-subjects variables in both datasets. Two-way interactions between Equipment and all other variables were included in the statistical General Linear and Analysis of Variance (ANOVA) models employed. All multiple pairwise comparisons in the results used the Tukey HSD method to control Type I Error. For all analyses, the maximum probability of Type I error (alpha) was .05 in significant results. Mean values for conditions are presented in parentheses.

Spacing Task Performance

The pilots’ VFR spacing task was to maintain at least the assigned spacing. Their IFR spacing task was to maintain the assigned spacing. The following factors were included in the statistical models used to analyze the VFR data: Equipment, Traffic, Flight Hours, Hood, and Approach. The IFR analyses included these factors: Equipment, Traffic, Flight Hours, Slowdown, and Approach. Both VFR and IFR analyses used models that included all two-way interactions with Equipment. For each pilot, the means of the absolute values of the differences between the assigned and actual spacing on each approach were analyzed.

A significant main effect of Equipment was found for the VFR approaches, $F(2, 61) = 6.01$, $p = .0041$. Multiple pairwise comparisons indicated that the mean spacing difference for the Baseline approaches (.37 NM, SD = .23) was significantly greater than the mean spacing difference for the Basic CDTI approaches (.20 NM, SD = .21) and for Range Monitor approaches (.18 NM, SD = .12). For the IFR approaches, the mean spacing differences for the Basic CDTI (.079 NM, SD = .039), Range Monitor (.083 NM, SD = .074), and Autopilot (.093 NM, SD = .052) conditions did not differ significantly.

Flight Technical Error

The factors included in the analyses of the FTE data were Equipment, Slowdown, Flight Hours, Traffic, Approach, and Subject. All two-way interactions with Equipment were included in the statistical models. The means of the absolute values of the horizontal deviations from the localizer and the means of the absolute values of the vertical deviations from the glide slope for each pilot and each instrument approach were analyzed. Results from autopilot approaches were excluded from these analyses because they did not measure pilot-related FTE.

No significant effects of Equipment, Traffic, Flight Hours, Approach, Slowdown, or interactions of the other factors with Equipment were found for the localizer deviations. The mean localizer deviations were .84 dots,[1] SD = .40 for the Baseline approaches, .67 dots, SD = .32 for the Basic CDTI approaches, and .75 dots, SD = .40 for the Range Monitor approaches. Significant main effects of Equipment, $F(2, 30) = 3.43$, $p = .045$ and Slowdown, $F(1, 30) = 5.33$, $p = .028$ were found for the glide slope deviations. Multiple pairwise comparisons did not find significant differences among the mean glide slope deviations for the Baseline (.85 dots, SD = .39), Basic CDTI (1.32 dots, SD = .46), and Range Monitor (.98 dots, SD = .93) approaches. Lead aircraft deceleration following the outer marker produced significantly larger glide slope

[1] A full-scale deflection is five dots.

Table 1. Experimental design. The follow symbols are used: V = VFR, I = IFR, C = Basic CDTI, R = Range Monitor (without autopilot), A = Autopilot (with Range Monitor), B = Baseline (no CDTI), S = Separate TTF deceleration and loss of visual contact, O = Overlapping TTF deceleration and loss of visual contact, N = No loss of visual contact; P = TTF deceleration prior to outer marker, F = TTF deceleration following outer marker, Traffic = Flights conducted from ACY, No Traffic = Flights conducted from SFM). The top portion shows the order of conditions for each subject.

	Approach Number							
Pilot ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Traffic 1	VRS	VCS	VBN	VBS	IRF	IAF	IBF	ICF
Traffic 2	VBS	VRS	VCS	VBN	ICF	IRF	IAF	IBF
Traffic 3	VBN	VBS	VRS	VCS	IAF	IBF	ICF	IRF
Traffic 4	VCS	VBN	VBS	VRS	IBF	ICF	IRF	IAF
Traffic 5	VRO	VCO	VBN	VBO	IRP	IAP	IBP	ICP
Traffic 6	VBO	VRO	VCO	VBN	ICP	IRP	IAP	IBP
Traffic 7	VBN	VBO	VRO	VCO	IAP	IBP	ICP	IRP
Traffic 8	VCO	VBN	VBO	VRO	IBP	ICP	IRP	IAP
No Traffic 1	VRS	VCS	VBN	VBS	IRF	IAF	IBF	ICF
No Traffic 2	VBS	VRS	VCS	VBN	ICF	IRF	IAF	IBF
No Traffic 3	VBN	VBS	VRS	VCS	IAF	IBF	ICF	IRF
No Traffic 4	VCS	VBN	VBS	VRS	IBF	ICF	IRF	IAF
No Traffic 5	VRO	VCO	VBN	VBO	IRP	IAP	IBP	ICP
No Traffic 6	VBO	VRO	VCO	VBN	ICP	IRP	IAP	IBP
No Traffic 7	VBN	VBO	VRO	VCO	IAP	IBP	ICP	IRP
No Traffic 8	VCO	VBN	VBO	VRO	IBP	ICP	IRP	IAP

	VFR						IFR							
Visual Contact	Basic CDTI		Range Monitor		Baseline		Basic CDTI		Range Monitor		Baseline		Autopilot	
Loss of Visual	O	S	O	S	O	S	F	P	F	P	F	P	F	P
No Loss					N									

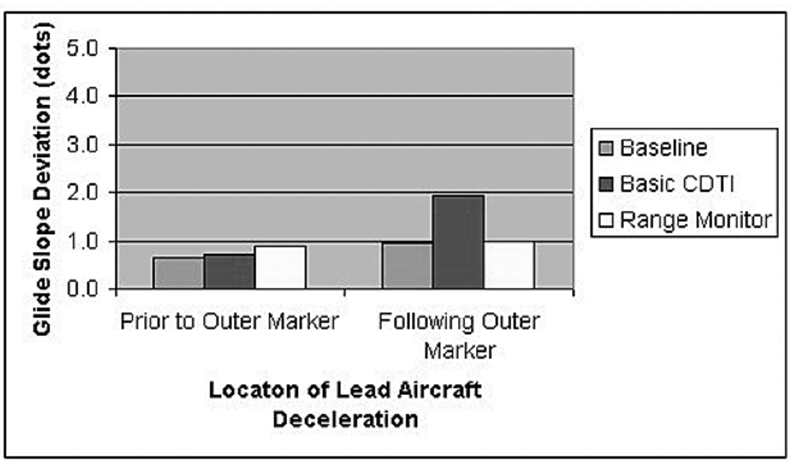

Figure 2. Effects of Equipment and Slowdown on glide slope deviation.

deviations (1.24 dots) than deceleration prior to the outer marker (.86 dots), $F(1, 30) = 8.27$, $p = .0074$. A significant interaction between Equipment and Slowdown was found, $F(2, 30) = 3.34$, $p = .049$. Tests for simple effects found a significant effect of Equipment when TTF decelerated following the outer marker, $F(2, 20) = 6.48$, $p = .0046$. Under these conditions, the mean deviations that occurred during Baseline (.96 dots), Range Monitor (1.00 dots), and Basic CDTI (1.93 dots) approaches differed significantly. The interaction of Equipment and Slowdown is presented in Figure 2.

Visual Reacquisition Time

Visual reacquisition time was measured following loss of visual contact on the downwind leg or on the final approach of the flight pattern. The factors included in the following analyses were Equipment, Traffic, Hood, Flight Hours, and Approach. All main effects and two-way interactions between Equipment and the other variables were included in the statistical models.

The analysis of downwind reacquisition times revealed no significant effects. The mean reacquisition times were 11.5 s for Baseline, 10.25 s for Basic CDTI, and 19.4 s for Range monitor approaches. The final approach visual reacquisition times showed a significant interaction of Equipment and Traffic (see Figure 2), $F(2, 33) = 3.79$, $p = .033$. Pilots using a Range Monitor CDTI that displayed TIS-B traffic visually re-acquired the TTF more quickly (4.1 s) than pilots using no traffic display (i.e., Baseline equipment, 18.2 s), $F(2, 21) = 7.32$, $p = .0039$. Use of the Basic CDTI showing other traffic led to a reacquisition time (9.5 s) that did not differ significantly from the Baseline or Range Monitor times. The three Equipment conditions did not differ significantly when only the TTF was displayed.

Eye Movements

Several analyses were conducted on pilot eye movement data. The allocation of visual attention was inferred from where the pilots directed their gaze. The analysis consists of a partitioning of the percentages of total dwell time found in various areas of interest: the aircraft instrument panel (Panel), the CDTI, the forward window (Window), other flight deck locations (Other), and areas that the coder was unable to determine (Unknown). The VFR allocation analysis excluded the head-down time that provided a loss of visual contact and the time spent visually re-acquiring the TTF. Allocation is treated descriptively and can be found in Figures 4 (VFR) and 5 (IFR). The second analysis was conducted on dwell time, the duration of individual dwells in particular areas of interest. The third analysis examined "look away" durations, that is, the time between dwells on particular areas of interest. "Head-down time," for example, can be defined as the time between dwells on Window during the VFR approaches.

Allocation of Visual Attention. Figure 4 shows the roughly 18% decrease in percentage of visual attention devoted to the Window area of interest when the pilot used a CDTI on VFR spacing approaches. A smaller (5%) reduction in attention to the Panel was also found. This analysis shows that the effect of the Basic CDTI on visual attention was the same as the Range Monitor during the VFR spacing task. Pilots looked at the CDTI about 27% of the time.

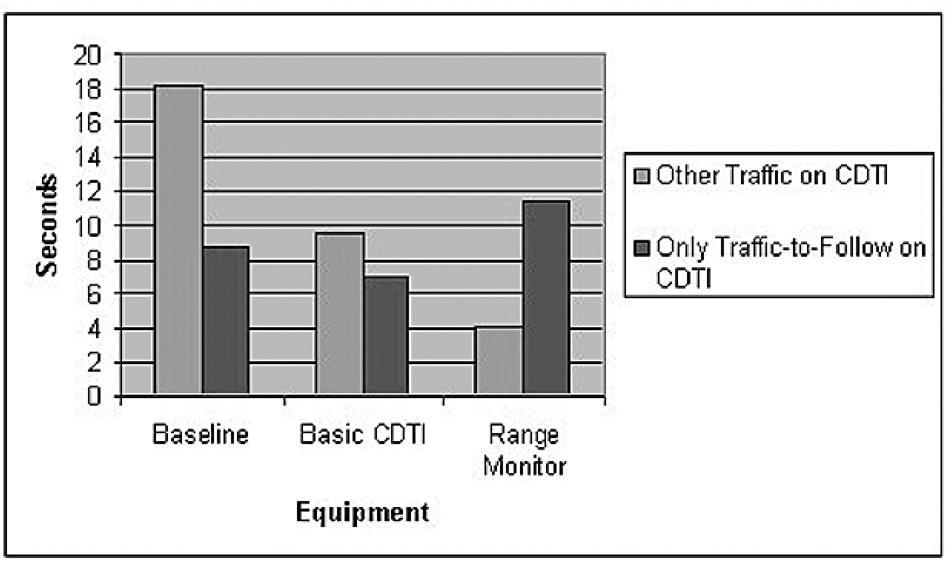

Figure 3. Effects of Equipment and Traffic on final approach visual reacquisition time.

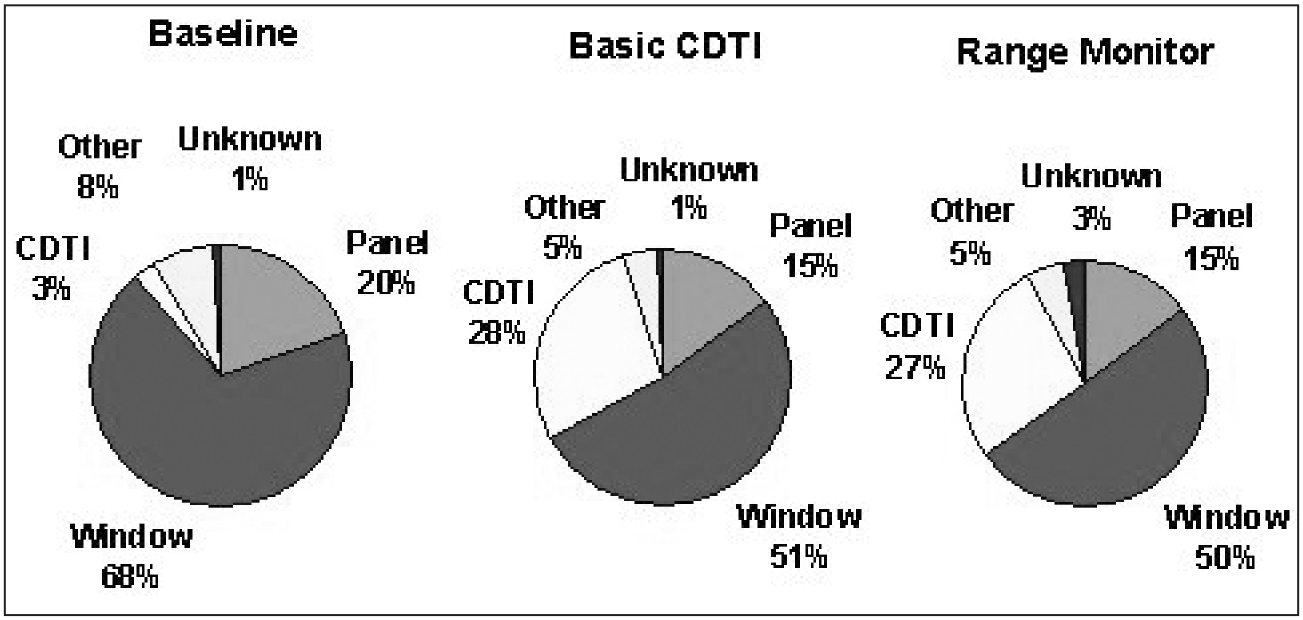

Figure 4. Allocation of visual attention during the VFR approaches.

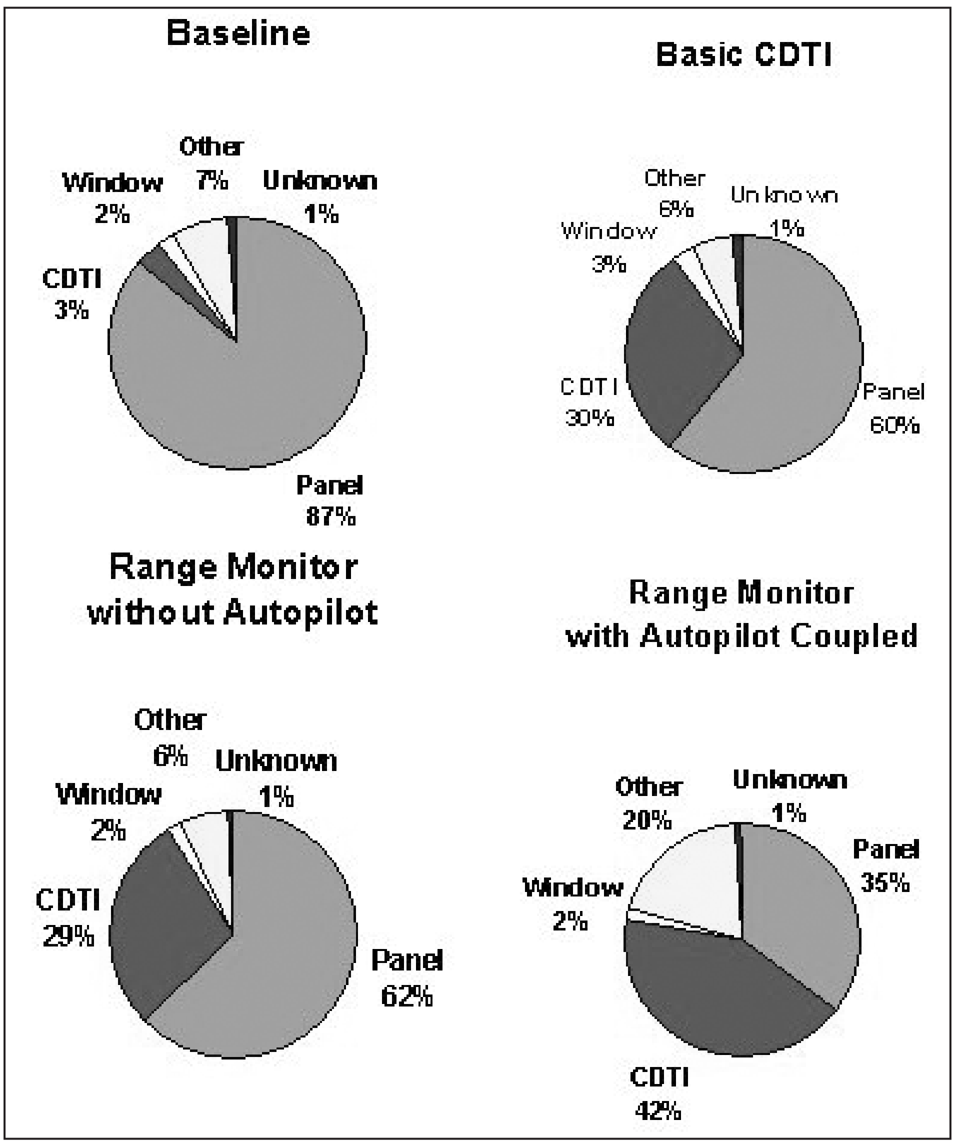

Figure 5. Allocation of visual attention during the IFR approaches.

Figure 5 shows how visual attention was allocated during the IFR spacing approaches. Pilots using a CDTI for IFR spacing devoted about 26% less attention to the instrument panel than they did on Baseline IFR approaches. As was found for VFR spacing, the Basic CDTI and Range Monitor affected attentional allocation virtually the same, receiving about 30% of the visual resources in either case. With Range Monitor and autopilot coupled, the Panel received more than fifty percent less attention than on the Baseline IFR approaches. An increase in attention to Other areas of interest and a further increase in attention to the CDTI also occurred when the autopilot was used in conjunction with the Range Monitor.

Dwell Time. The mean dwells on Window, CDTI, and Panel during each VFR approach were analyzed with statistical models consisting of the following factors: Equipment, Traffic, Approach, Hood, Flight Hours, Subject, and the interactions of Equipment with Traffic, Approach, Slowdown, and Flight Hours. The main effect of Equipment on Window dwell was significant, $F(2,29) = 24.82$, $p < .0001$. Multiple pairwise comparisons revealed significant differences between the durations of the dwells that occurred during the VFR Baseline (8.9 s) approaches and those that occurred during the Basic CDTI (6.0 s) and Range Monitor (5.5 s) approaches. The main effect of Hood was significant as well, $F(2, 26) = 18.08$, $p < .0001$. The mean dwells on Window were longer with no loss of visual contact (8.8 s) than with separate (6.9 s) or overlapping (6.8 s) loss of visual contact and lead aircraft deceleration. The analysis revealed a significant effect of Approach, $F(3, 26) = 3.40$, $p = .033$. The mean Window dwell time increased with each approach with the mean dwell duration during the fourth approach (8.1 s) significantly longer than during the first (6.9 s). The interaction of Approach and Equipment was significant, $F(6, 26) = 6.52$, $p = .0003$. This interaction is shown in Figure 6. The analysis of dwell duration for CDTI during VFR spacing did not find any significant differences.

The mean dwell durations on CDTI and Panel during each IFR approach were analyzed with statistical models consisting of the following factors: Equipment, Traffic, Approach, Slowdown, Flight Hours, Subject, and the interactions of Equipment with Traffic, Approach, Slowdown, and Flight Hours. The results for dwell on the CDTI showed a significant main effect of Equipment, $F(3, 23) = 9.92$, $p = .0002$. Multiple pairwise comparisons indicated that the mean CDTI dwells found during the Baseline approaches (1.8 s) were significantly different from the dwells on the Range Monitor (2.9 s), Basic CDTI (3.0 s), and Range Monitor with Autopilot (3.4 s) approaches. Note that the CDTI was not operating during the Baseline IFR or VFR approaches.

Significant main effects of Equipment, $F(3, 60) = 25.79$, $p < .0001$, and Approach, $F(3, 33) = 6.42$, $p = .0015$ were found for the mean dwells on the instrument panel that were recorded during IFR spacing. Multiple pairwise comparisons indicated that with the Baseline equipment, dwells were significantly longer (17.1 s) than with the Basic CDTI (4.9 s), the Range Monitor (5.3 s), or Range Monitor with Autopilot (3.1 s). The instrument panel dwells were significantly longer on Approach 5 (10.0 s) than on Approach 6 (5.6 s) or Approach 8 (6.2 s). The interaction of Equipment and Approach was also significant, $F(12, 33) = 19.91$, $p < .0001$, as shown in Figure 7.

Look Away Duration. The mean look away durations for each pilot and each approach were analyzed. Differences among the Window look away durations that were found on Baseline (5.6 s), Basic CDTI (6.3 s), and Range Monitor (5.7 s) approaches were not significant.

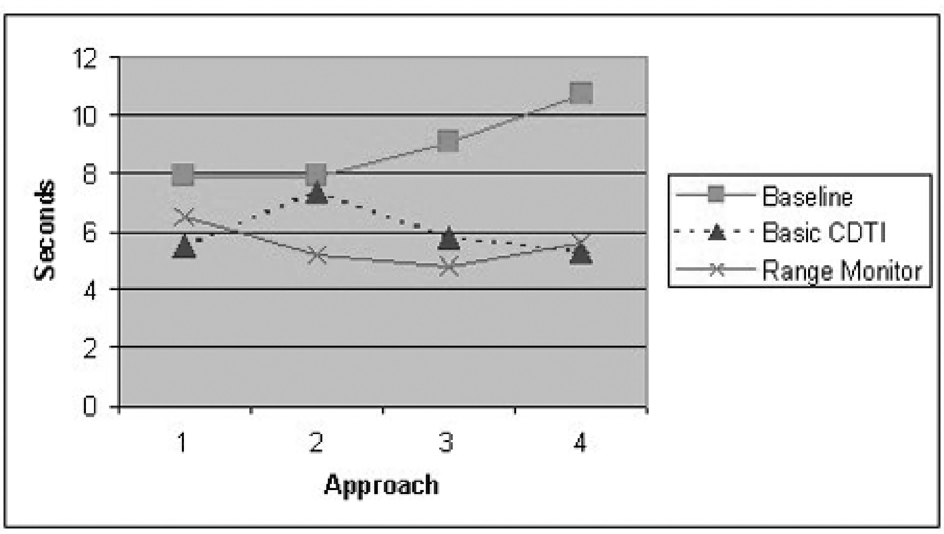

Figure 6. Window dwell time for VFR approaches.

The effect of Approach was significant, F (3, 35) = 4.93, p = .0058. Multiple pairwise comparisons found that the mean head-down time on the third approach (7.6 s) was longer than on the first or second approach (both 5.1 s). A significant interaction between Equipment and Hood was found, F (2, 35) = 3.55, p = .040. This interaction effect is shown in Figure 8. Tests for simple effects found a significant effect of Hood for Basic CDTI equipment, P (1, 35) = 4.40, p = .043. When the pilot used the Basic CDTI for VFR spacing, head-down time was longer on approaches when the loss of visual contact overlapped the TTF deceleration (8.3 s) than when they occurred separately (4.3 s).

The analysis of look away duration for CDTI excluded the times that were found between fixations on CDTI during Baseline approaches. The mean CDTI look away duration for Basic CDTI approaches (13.4 s) did not differ significantly from the mean CDTI look away duration for Range Monitor approaches (11.6 s). A significant main effect of Traffic was found, F (1, 30) = 15.87, p = .0004. Pilots looked away from the CDTI on average for 28.9 s when it did not show additional TIS-B traffic and looked away for 17.3 s when it showed the additional traffic. The interaction between Equipment and Traffic was significant for Panel look away duration, F (2, 29) = 4.44, p = .021(see Fig. 9). Tests for simple effects found significant differences for Equipment when only the TTF was displayed. Multiple pairwise comparisons indicated that when the Range Monitor was used for VFR spacing, the time between Panel fixations was longer (24.9 s) than when the Basic CDTI (15.5 s) or Baseline equipment (15.0 s) was used. A significant effect of Flight Hours

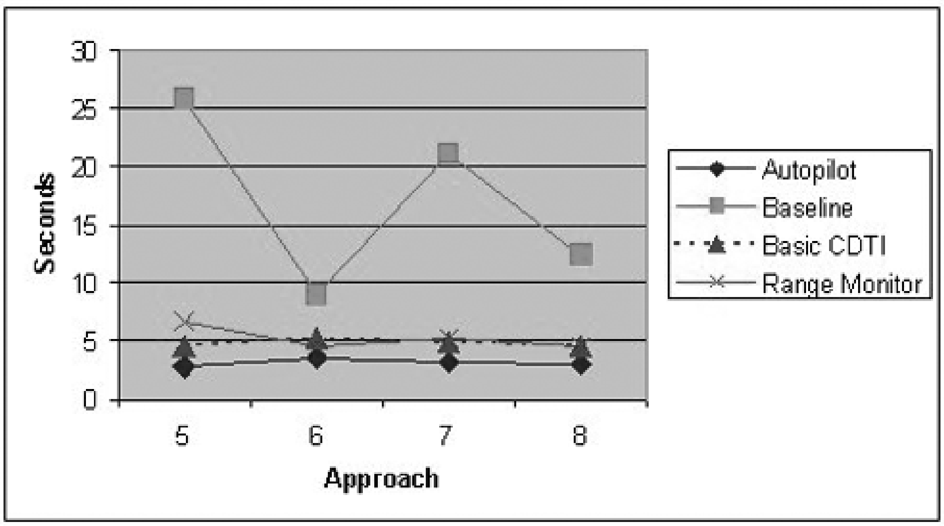

Figure 7. Instrument panel dwell time for IFR approaches.

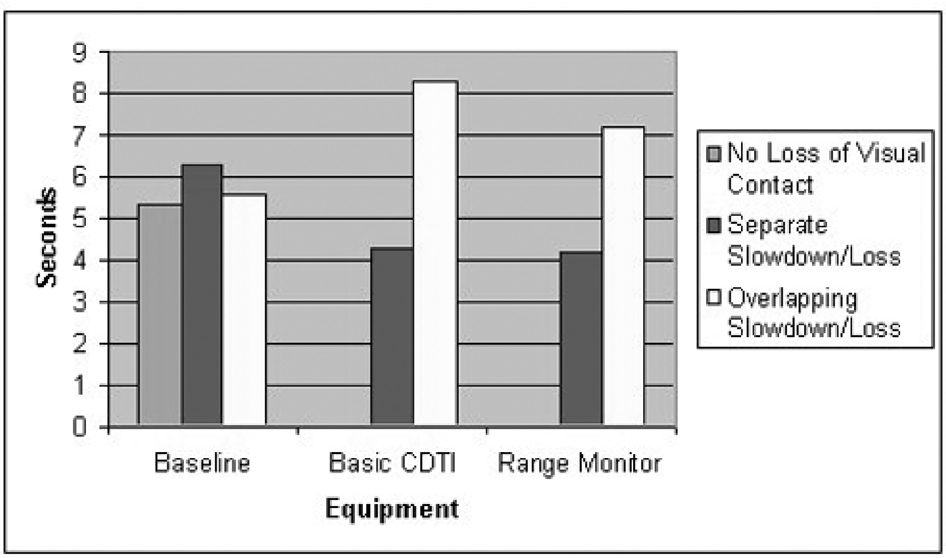

Figure 8. Window look away duration (head-down time) for VFR approaches.

was found, $F(1, 42) = 6.04$, $p = .018$. Low flight-hour pilots showed a longer look away duration for Panel (19.4 s) than pilots with high flight hour (15.5 s) during VFR spacing.

The time between fixations on the CDTI during the IFR approaches showed a significant main effect of Equipment, $F(2, 30) = 8.97$, $p = .0009$. The mean look away duration for CDTI was longer during the approaches with the Basic CDTI (11.0 s) and Range Monitor without autopilot (11.2 s) than during the approaches with Range Monitor and autopilot coupled (6.1 s). A significant effect of Slowdown, $F(1, 43) = 6.17$, $p = .017$, reflected lengthier times between fixations on the CDTI during approaches during which the lead aircraft decelerated following the outer marker (5.9 s) than prior to it (4.1 s). A significant effect of Traffic, $F(1, 43) = 5.14$, $p = .028$, indicated that pilots whose CDTI only showed the TTF looked away from the CDTI for a longer duration (5.8 s) than pilots whose CDTI displayed all other traffic within range (4.2 s).

The time between fixations on the instrument panel showed a significant main effect of Equipment, $F(3, 30) = 12.58$, $p < .0001$. The mean look away duration for Panel was longer during the Range Monitor approaches with autopilot coupled (8.6 s) than during the Range Monitor approaches conducted without autopilot (4.4 s), the Basic CDTI approaches (4.4 s), or the Baseline approaches (2.8 s). In other words, on the IFR approaches with autopilot coupled, the pilots looked at the CDTI more frequently and at the instrument panel less frequently than in the other Equipment conditions.

A significant interaction between Equipment and Approach was found in the time between fixations on the instrument panel for the IFR approaches, $F(15, 46) = 2.32$, $p = .015$. This interaction is shown in Figure 10.

Significant effects of Equipment occurred on Approach 8, $F(3, 46) = 3.49$, $p = .023$. Pilots looked away from the instrument panel significantly longer when using the Range Monitor Tool with autopilot coupled (9.0 s) than when using the Range Monitor Tool without autopilot

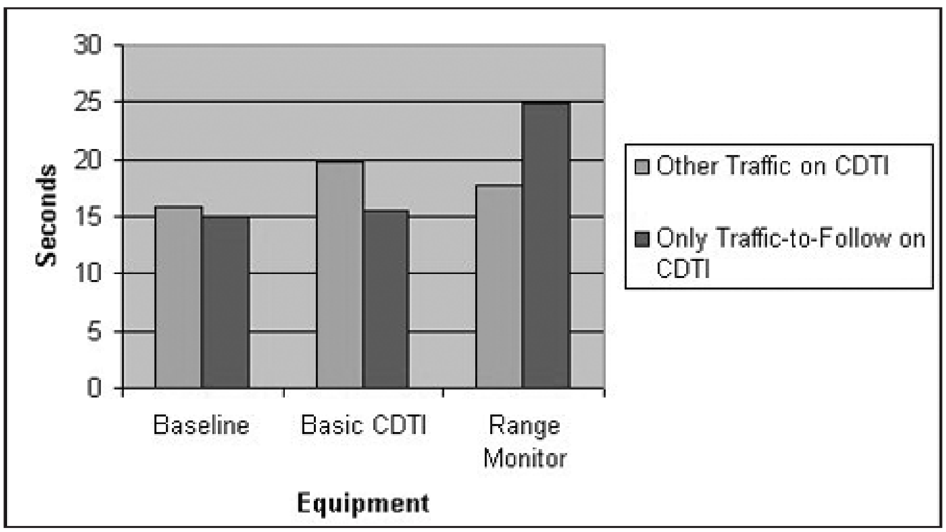

Figure 9. Effect of Traffic and Equipment on instrument panel look away duration for VFR approaches.

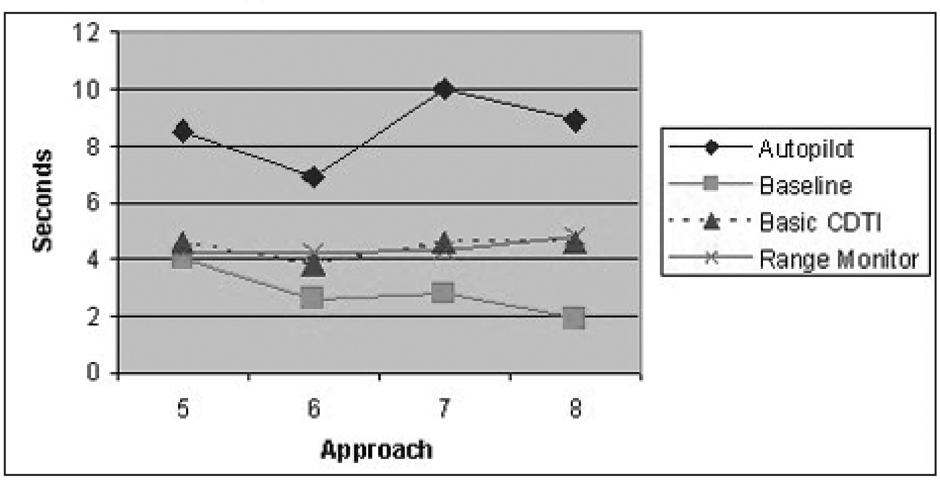

Figure 10. Effect of approach and Equipment on instrument panel look away duration for IFR approaches.

(4.8 s), Basic CDTI (4.6 s), or when using Baseline equipment (1.9 s).

Subjective Workload Ratings

The NASA-TLX was used to assess self-rated pilot workload following each approach. This instrument requires ratings along six workload dimensions on a scale of 0 to 100: mental demand, physical demand, frustration level, own performance, temporal demand (time pressure), and effort. The following factors were included in the analyses of the VFR workload ratings: Equipment, Hood, Subject, Hours, Traffic, and Approach. These factors were included in the models used to analyze the IFR workload ratings: Equipment, Slowdown, Subject, Hours, Traffic, and Approach. The two-way interactions of Equipment and each other variable were included in the statistical models. For each dimension, the results of the VFR approaches are presented followed by those of the IFR approaches.

Mental Demand. Mental demand from the VFR approaches, as an interaction of Equipment and Hood, was significant, $F (2, 31) = 5.32$, $p = .010$. The interaction is shown in Figure 11. Tests for simple effects found significant differences in mental demand for Equipment only for Separate Hood approaches, $F (2, 31) = 4.45$, $p = .020$, and for Hood, only for Basic CDTI approaches, $F (1, 31) = 9.13$, $p = .0050$. For the Separate Hood approaches, mean CDTI condition mental demand (61.9) was higher than Baseline mental demand (46.6). Workload was rated higher during the Separate condition than during the Overlap condition (39.4) on the CDTI approaches. Examination of the raw data indicated that two subjects provided relatively low workload ratings on all approaches. They had both been assigned to the Overlap Hood condition.

In the ratings from the IFR approaches, the effect of Equipment on mental demand was significant, $F (3, 29) = 26.43$, $p < .0001$. Multiple comparisons found that pilots reported significantly higher mental demand (65.9) during approaches using the Basic CDTI and significantly lower mental demand (43.1) on Autopilot approaches compared to Baseline approaches (53.1). Significant differences were not found between the Baseline and Range Monitor (58.8) approaches. A significant Equipment by Approach interaction was found for mental demand $F (9, 29) = 7.01$, $p <.0001$, as shown in Figure 12.

Physical Demand. The VFR physical demand ratings resulted in a significant interaction between Equipment and Hood, $F (2, 31) = 3.47$, $p = .044$, as shown in Figure 13. Examination suggests that differences in Hood under Baseline conditions produced this interaction effect. A significant effect of Equipment was found in the analysis of the physical workload dimension for the IFR approaches, $F (3, 45) = 15.82$, $p < .0001$. This effect resulted from lower ratings in the Autopilot condition (31.6) than in the Baseline (44.1), Basic CDTI (48.1), and Range Monitor (48.1) conditions.

Temporal Demand. The analysis of temporal demand (time pressure) for the IFR approaches revealed significant main effects of Equipment, $F (3,30) = 8.23$, $p = .0004$ and Traffic, $F (1, 40) = 5.02$, $p = .03$. Multiple comparisons found that pilots reported significantly higher temporal demand during approaches using the Basic CDTI (46.8) compared to the Baseline (36.9) and Autopilot (31.3) approaches, which did not differ significantly from one another. Significant differences were not found between the Baseline and Range Monitor (44.3) approaches, although the approaches conducted using the Range Monitor (without autopilot) were rated significantly higher in temporal demand than those conducted using

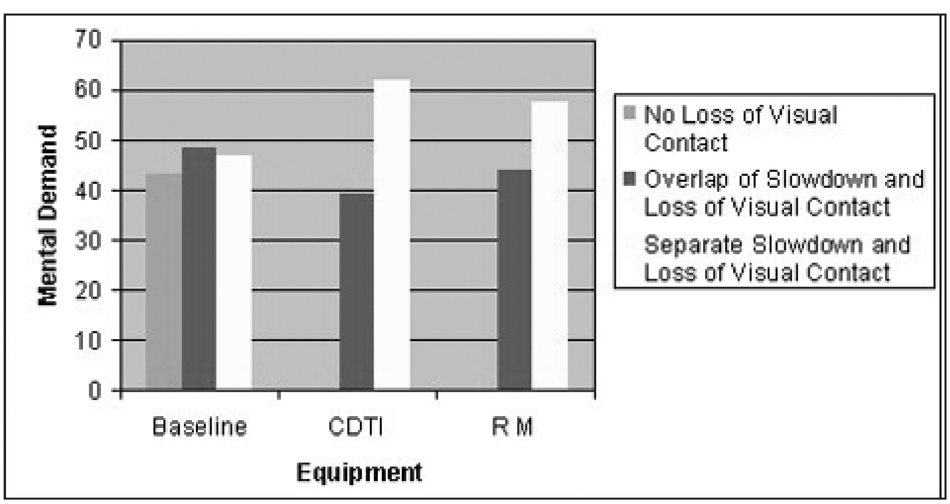

Figure 11. Mental demand on VFR approaches.

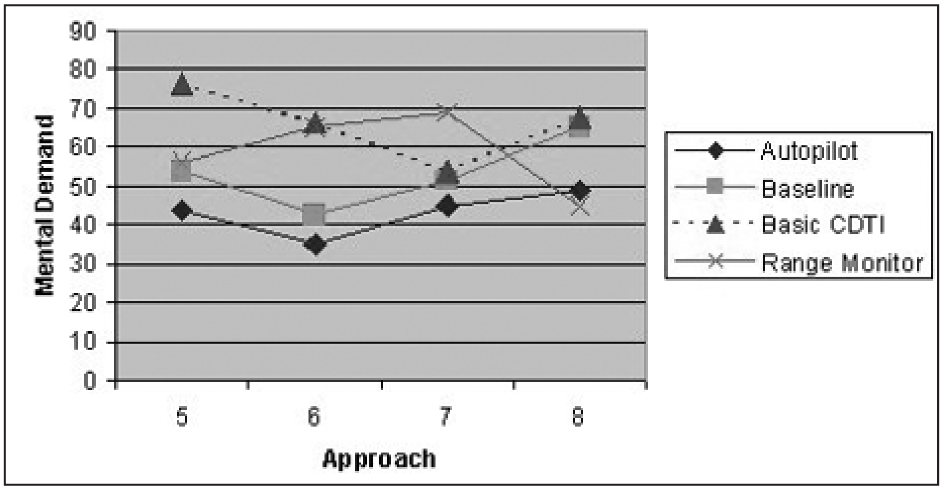

Figure 12. Mental demand on IFR approaches.

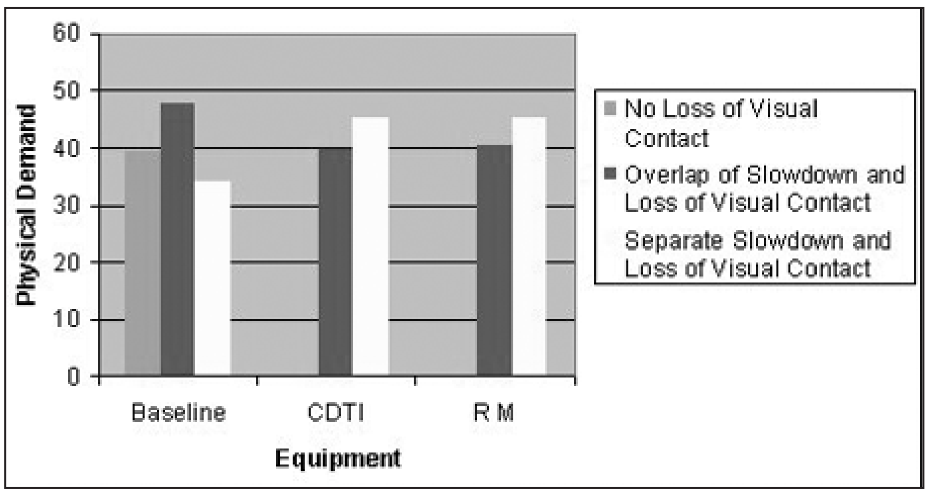

Figure 13. Physical demand on VFR approaches.

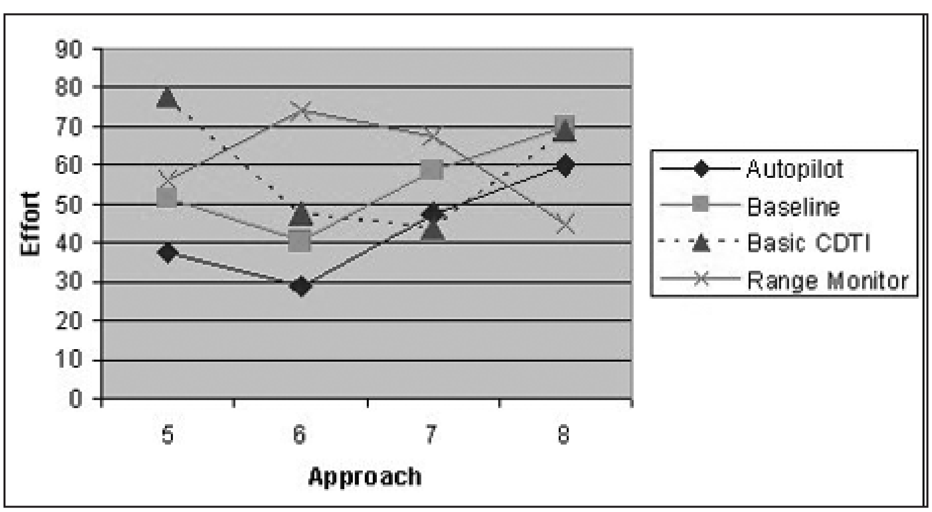

Figure 14. Effort on IFR approaches.

Autopilot. There was more temporal demand with additional traffic displayed (45.9) than with only the traffic-TTF displayed (33.8).

Own Performance. Unlike the other TLX workload dimensions, higher ratings of Performance indicate lower workload. The VFR ratings of own performance resulted in significant main effects of Traffic, $F(1, 30) = 30.37$, $p < .0001$, Flight Hours, $F(1, 58) = 18.14$, $p < .0001$, and Equipment, $F(2, 30) = 5.44$, $p = .010$. Own performance using the basic CDTI (70.8) or the Range Monitor (70.3) was rated higher than Baseline performance (64.1). Performance was rated higher (i.e., less workload) following approaches with only the TTF displayed (72.8) than with additional traffic (61.9). High-hour pilots rated their performance higher (75.6) than low-hour pilots (59.1).

The analysis of Performance ratings on the IFR approaches indicated significant main effects of Slowdown, $F(1, 40) = 8.33$, $p = .006$, and Flight Hours, $F(1, 56) = 15.00$, $p = .0003$. The pilots rated their own performance higher when the lead aircraft slowed prior to the outer marker or OM (76.3) than when it slowed following OM (61.7). High-hour pilots rated their performance higher (77.6) than did low-hour pilots (60.5).

Effort. A significant main effect of Flight Hours was found in the VFR Effort workload ratings, $F(1, 58) = 4.04$, $p = .049$. Pilots with low Flight Hours reported higher Effort (59.2), compared to pilots with high Flight Hours (48.5).

Significant main effects of Equipment, $F(3, 45) = 5.38$, $p = .0030$, Traffic, $F(1, 40) = 4.96$, $p = .031$, and Approach, $F(3, 36) = 3.98$, $p = .015$, were found in the IFR results for the Effort workload dimension. The interaction of Equipment and Approach was also significant for Effort, $F(6, 36) = 3.06$, $p = .010$ (see Fig. 14). Pilots flying with the Range Monitor and autopilot coupled rated their effort lower (43.4) than pilots flying manually with the Range Monitor (60.6) or with the Basic CDTI (59.4). Pilots for whom other traffic was displayed rated their effort higher (61.0) than pilots who had only the TTF displayed (48.3). No significant differences in rated effort between the Baseline (55.1) and other conditions were found. Figure 14 presents the significant interaction of Equipment and Approach.

Frustration. For the frustration workload dimension, a significant interaction was found between Equipment and Slowdown, $F(6, 42) = 3.19$, $p = .011$ for the IFR approaches. Differences among the four Equipment conditions were significant only for approaches where the TTF slowed prior to OM, $F(3, 21) = 4.00$, $p = .021$. Frustration was rated higher during manually flown approaches with the Range Monitor (46.9) than on approaches using the Range Monitor with coupled Autopilot (25.0). The ratings obtained under these conditions did not differ significantly from those obtained after Basic CDTI (34.4) or Baseline (29.4) approaches.

Questionnaire

The questionnaires consisted of statements that the participating pilots responded to by circling a number between one and five (see Table 2). Separate questionnaires were administered following the four VFR approaches and following the four IFR approaches.

Table 2. Questionnaire rating scale.

Rating	Text
1	Strongly Disagree
2	Somewhat Disagree
3	Neither Agree nor Disagree
4	Somewhat Agree
5	Strongly Agree

Some of the statements pertained to the same aspect of task performance under the various Equipment conditions. For example, three VFR questionnaire items concerned the ease of noticing the decelerations of the TTF when not using a CDTI (Baseline), when using the Basic CDTI, and when using the Range Monitor Tool. Statistical tests were employed to compare results within these sets of questions. Statistical tests were conducted comparing responses from the pilots using equipment that only showed the TTF with those using equipment that also showed other traffic and on the statistical interactions of Equipment with Traffic and Flight Hours. Tests of the significance of the effects of Traffic, Flight Hours, and the interaction of these variables were also conducted on the responses to items that were not repeated for different Equipment conditions. The following results are presented in sections that pertain to spacing task performance, situation awareness, and usability.

Performance Items

Table 3 presents the questionnaire statements and descriptive statistics, the mean and standard deviation (SD), for the VFR spacing task performance items. Mean ratings indicate that the participants somewhat (3.5 – 4.4) or strongly (4.5 – 5.0) agreed, neither agreed nor disagreed (2.5 – 3.4), or that they somewhat (1.5 – 2.4) or strongly (1.0 – 1.5) disagreed with the statement. Table 4 presents the statements and results for the IFR spacing task performance items.

The items concerned with the pilot's ability to perform the VFR spacing task when the TTF was not in sight out-the-window or when the TTF moved outside the Range Monitor Tool's lateral coverage yielded a significant interaction between Flight Hours and Traffic, F

Table 3. Questionnaire Results for VFR Spacing Task .

Statement	Mean	SD
The CDTI aided my visual reacquisition of the TTF after the hood was raised.[1]	4.6	.63
I could perform the VFR spacing task when the TTF was in sight out-the-window and I was using the Range Monitor Tool.	4.4	.89
I could perform the VFR spacing task when the TTF was NOT in sight out-the-window (with hood lowered) and I was using the Range Monitor Tool.	4.4	.62
With the Range Monitor Tool, I was able to adjust to the decelerations of the TTF soon enough to avoid an unacceptable overtake.	4.4	.50
I could perform the VFR spacing task when the TTF was in sight out-the-window and I was using the Basic CDTI.	4.3	.60
I could perform the VFR spacing task when the TTF was NOT in sight out-the-window (with hood lowered) and I was using the Basic CDTI.	4.1	.93
With Basic CDTI, I was able to adjust to the decelerations of the TTF soon enough to avoid an unacceptable overtake.	4.1	.89
I could perform the VFR spacing task when the TTF moved outside the Range Monitor Tool's lateral coverage (e.g., when the TTF turned final)	3.9	.57
I was able to adjust CDTI display range as often as I needed during the VFR spacing task.	3.7	.95
While I was using the Basic CDTI, the VFR spacing task interfered with my instrument scan.	2.5	1.0
While I was using the Range Monitor Tool, the VFR spacing task interfered with my instrument scan.	2.5	1.1
While I was using the Basic CDTI, the VFR spacing task interfered with my out-the-window scan.	2.3	1.0
While I was using the Range Monitor Tool, the VFR spacing task interfered with my out-the-window scan.	2.3	1.2

[1] References to the instrument flight training hood were understood by the pilots as pertaining to the head-down interval

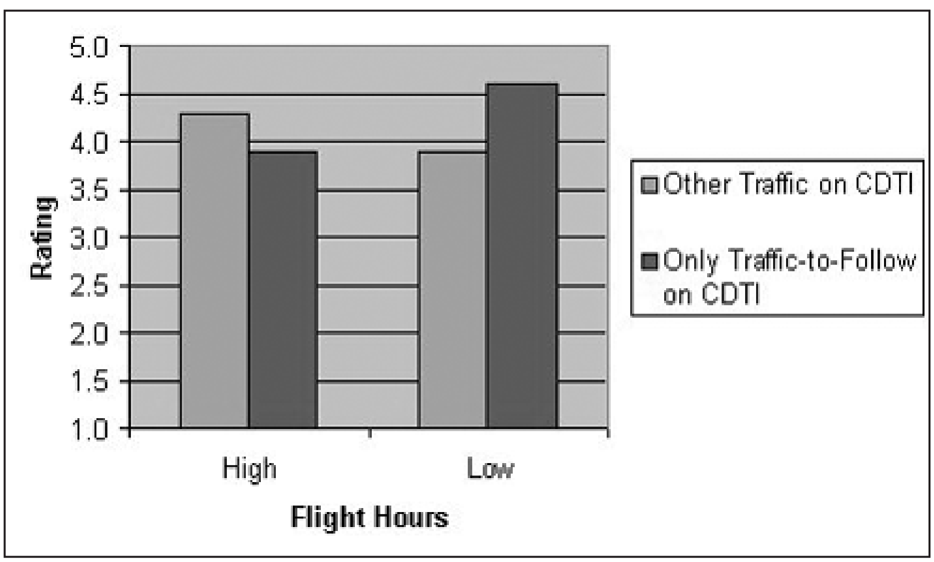

Figure 15. Ability to perform the VFR spacing task when TTF was not in sight out-the-window or when the TTF moved outside the Range Monitor Tool's lateral coverage.

(1, 36) = 5.75, p = .022. Tests for simple effects found a significant effect of Flight Hours for pilots whose displays only showed the TTF, F (1, 36) = 4.26, p = .046 and a significant effect of Traffic for low flight-hour pilots, F (1, 36) = 4.26, p = .046. This interaction effect is shown in Figure 15. Low flight-hour pilots whose CDTI showed only the TTF agreed more strongly that they could perform the task than high flight-hour pilots whose CDTI showed only the TTF. Low flight-hour pilots, whose CDTI showed only the TTF, agreed more strongly that they could perform the task than low flight-hour pilots whose displays also showed other traffic.

Pilots differed significantly in their agreement with the statement that the CDTI aided their visual reacquisition of the TTF after the hood was raised, depending upon whether their CDTI showed traffic in addition to the TTF or only the TTF, F (1, 12) = 5.51, p = .037. The pilots using a CDTI that only showed the TTF agreed more strongly with the statement (4.9) than the pilots whose CDTI also showed other traffic (4.2).

The pilots whose displays only showed the TTF agreed more strongly (4.7) that they could perform the IFR spacing task than the pilots whose displays showed other traffic (4.1), F (1, 36) = 6.36, p = .016. Similarly, pilots whose displays only showed the TTF disagreed more (2.1) with the item stating that the IFR spacing task interfered with their ability to fly a precise ILS approach than the pilots whose displays also showed other traffic (2.8), F (1, 36) = 4.97, p = .032. A significant interaction between Flight Hours and Traffic was found for these items, F (1,36) = 7.85, p = .0081. As shown in Figure 16, high-hour pilots with only the TTF on the CDTI disagreed more strongly (1.5) with the statement that the task interfered than low-hour pilots with only the TTF on the CDTI (2.7), F (1, 36) = 5.91, p = .020. Also, high-hour pilots without other traffic displayed disagreed more strongly (1.5) with the statement than high-hour pilots with other traffic shown on the CDTI (3.2), F (1, 36) = 12.65, p = .0011.

The set of items stating that the IFR spacing task interfered with the pilot's instrument scan produced a significant interaction between Flight Hours and Traffic, F (1, 35) = 4.15, p = .049 (Fig. 17). Tests for simple effects found significant differences in Traffic for pilots with high flight hours, F (1, 35) = 8.28, p = .0068, and in Flight Hours for pilots whose display included all of the traffic that was within range, not just the TTF, F (1, 35) = 5.51, p = .025. High-hour pilots with no other traffic on the CDTI disagreed more (2.2) than high-hour pilots with other traffic (3.6) that the IFR spacing task interfered with their instrument scan. Low-hour pilots with other traffic displayed also disagreed more (2.3) that the task interfered with their instrument scan than high-hour pilots with other traffic displayed.

Situational Awareness Items

Table 5 presents the questionnaire statements and descriptive statistics for the VFR spacing task situational awareness items. Table 6 presents this information for the IFR situational awareness items.

A significant main effect of Traffic was found for responses to the VFR spacing task statements which state

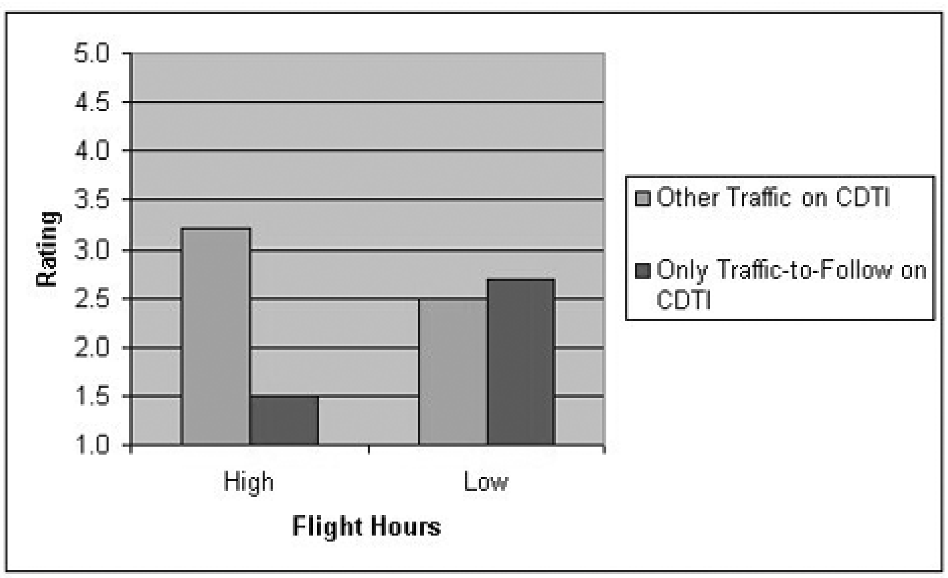

Figure 16. IFR spacing task interference with ability to fly a precise ILS approach.

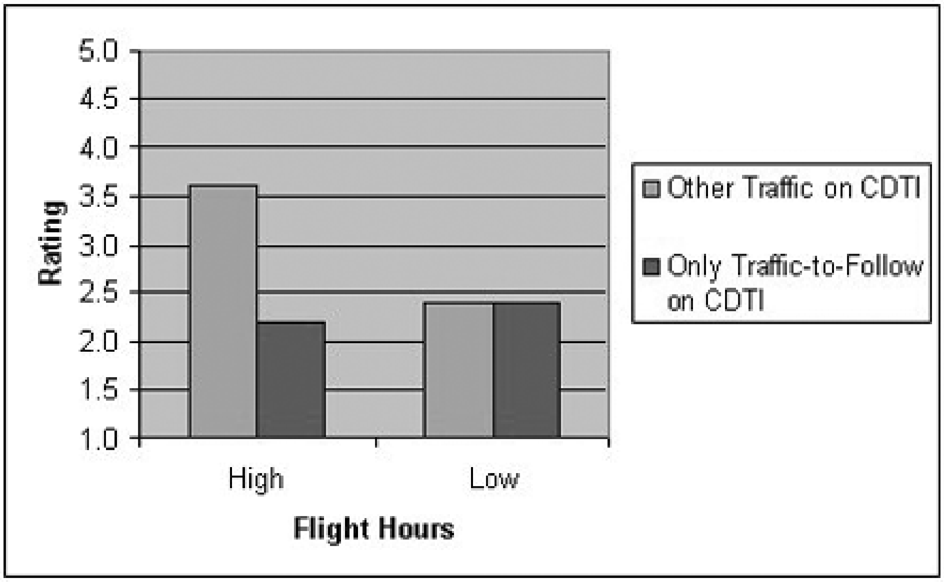

Figure 17. IFR spacing task interference with pilot instrument scan.

Table 4. Questionnaire Results for IFR Spacing Task Performance.

Statement	Mean	SD
I could perform the IFR spacing task when I was using the Range Monitor Tool and autopilot coupled.	4.7	.48
I could perform the IFR spacing task when I was using the Range Monitor Tool without autopilot.	4.4	.81
When using the Range Monitor Tool for the IFR spacing task (performed without autopilot), I was able to adjust to the decelerations of the TTF soon enough to avoid an unacceptable overtake.	4.3	.86
I could perform the IFR spacing task when I was using the Basic CDTI.	4.2	.98
When using the Basic CDTI for the IFR spacing task, I was able to adjust to the decelerations of the TTF soon enough to avoid an unacceptable overtake.	4.1	.89
While I was using the Basic CDTI, the IFR spacing task interfered with my instrument scan.	3.1	1.24
While I was using the Range Monitor Tool, the IFR spacing task (performed without autopilot) interfered with my instrument scan.	2.6	1.18
While I was using the Basic CDTI, the IFR spacing task interfered with my ability to fly a precise ILS approach.	2.6	1.31
While I was using the Range Monitor Tool, the IFR spacing task (performed without autopilot) interfered with my ability to fly a precise ILS approach.	2.4	1.32
While I was using the Range Monitor Tool, the IFR spacing task (performed with autopilot coupled) interfered with my instrument scan.	2.1	1.00
While I was using the Range Monitor Tool, the IFR spacing task (performed with autopilot coupled) interfered with my ability to fly a precise ILS approach..	1.9	1.12

that when the TTF was flying straight ahead (or turning), its bearing relative to ownship was accurately shown on the CDTI, $F(1, 24) = 25.73$, $p < .0001$. Pilots whose CDTIs only showed the TTF agreed significantly more strongly (4.9) that the relative bearing of the TTF was accurately displayed than the pilots whose displays also showed other traffic (4.1).

Items stating that it was easy to notice decelerations of the TTF during the VFR approaches showed a significant effect of Equipment, $F(2, 36) = 24.23$, $p < .0001$. Multiple pairwise comparisons indicated that pilots using Baseline equipment disagreed significantly more strongly (2.0) with the statement than when they were using the Basic CDTI (3.6) or Range Monitor Tool (4.3). A significant interaction of Flight Hours and Traffic was also found, $F(1, 36) = 5.13$, $p = .030$. The interaction is presented in Figure 18. Tests for simple effects found a significant effect of Flight Hours for pilots whose displays showed other traffic in addition to the TTF, $F(1, 36) = 6.51$, $p = .015$. Among the pilots who used displays that showed other traffic, those with high flight hours agreed more strongly (3.9) that it was easy to notice the decelerations than the low-hour pilots (2.9).

Usability Items

Table 7 presents the statements and descriptive statistics for the VFR spacing task usability items. The statements and descriptive statistics for the IFR spacing task can be found in Table 8.

Low- and high-hour pilot responses differed with regard to the use of certain CDTI features during VFR spacing. Low-hour pilots agreed significantly more strongly (4.8) than the high-hour pilots (4.2) that they used of the numerical range of the selected TTF during the VFR spacing task, $F(1, 12) = 9.67$, $p = .009$. High-hour pilots agreed more strongly (4.1) than low-hour pilots (2.6) that they set and used the range ring when performing the VFR spacing task with the Range Monitor Tool, $F(1, 12) = 9.92$, $p = .0084$. Also, pilots using a CDTI that showed other traffic agreed more strongly (3.9) than pilots whose display only showed the TTF (2.8) that they set and used the range ring for VFR spacing, $F(1, 12) = 5.42$, $p = .038$.

A statistically significant interaction between Equipment and Flight Hours was found for the items stating that the VFR spacing task resulted in an acceptable amount of workload when performed with the Basic CDTI or Range Monitor Tool, $F(1, 24) = 4.23$, $p = .049$. This interaction is shown in Figure 19. Tests for simple effects indicated that the difference due to Flight Hours was significant only for responses to the Basic CDTI statement, $F(1, 24) = 5.09$, $p = .034$, and not for the Range Monitor Tool responses. High flight-hour pilots using the Basic CDTI agreed more strongly (4.6) that workload was acceptable during VFR spacing than low-hour pilots using the Basic CDTI (3.9). Tests for simple effects also found a significant effect of Equipment for low flight-hour pilots, $F(1, 24) = 4.65$, $p = .041$. Low flight-hour pilots using the Range Monitor responded more strongly (4.6) that workload was acceptable than low-hour pilots using the Basic CDTI (3.9).

Responses to the statement that the spacing tools on the Range Monitor Tool added clutter without adding substantial benefit produced a significant main effect of Flight Hours, $F(1, 12) = 4.82$, $p = .049$. Low-hour pilots disagreed more strongly (1.8) with the statement than

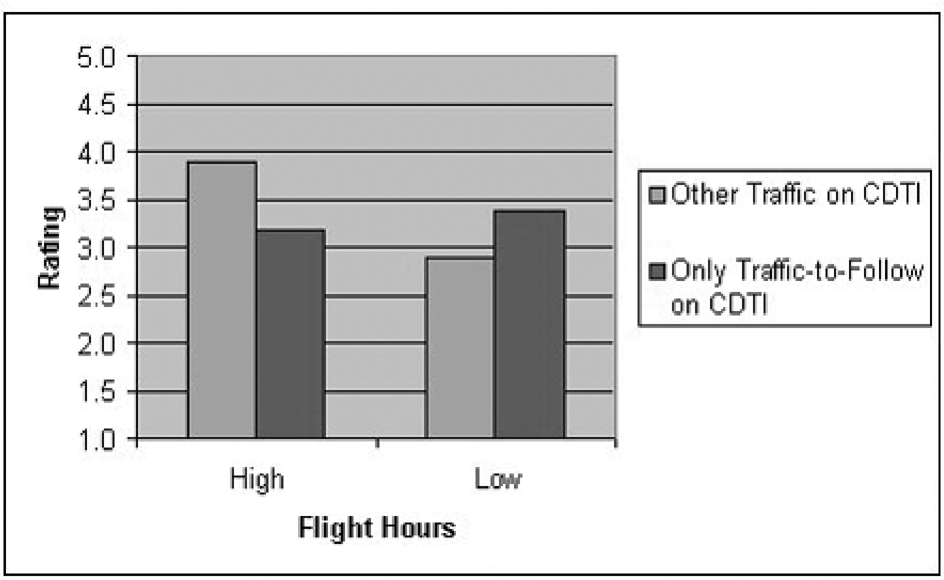

Figure 18. Ease of noticing the decelerations of the TTF during VFR spacing task performance.

Table 5. Questionnaire Results for VFR Spacing Task Situational Awareness.

Statement	Mean	SD
The Basic CDTI helped me to re-acquire the TTF after the hood was raised.	4.8	.45
When the TTF was flying straight ahead, its bearing relative to ownship was accurately shown on the CDTI.	4.7	.48
The Range Monitor Tool helped me to re-acquire the TTF after the hood was raised.	4.6	.63
When the TTF was turning, its bearing relative to ownship was accurately shown on the CDTI.	4.4	.72
My awareness of ownship position was acceptable while I used the CDTI to perform the VFR spacing task.	4.4	.62
It was easy to notice the decelerations of the TTF when using the Range Monitor Tool.	4.3	.58
I was sufficiently aware of nearby traffic while I was performing the VFR spacing task using the Range Monitor Tool.	4.1	1.02
I was sufficiently aware of nearby traffic while I was performing the VFR spacing task using the Basic CDTI.	4.0	1.10
It was easy to notice the decelerations of the TTF when using the Basic CDTI.	3.6	1.02
It was easy to notice the decelerations of the TTF when not using a CDTI.	2.0	1.03

Table 6. Questionnaire Results for IFR Spacing Task Situational Awareness.

Statement	Mean	SD
My awareness of ownship position was acceptable while I used the Basic CDTI to perform the IFR spacing task.	4.4	.62
My awareness of ownship position was acceptable while I used the Range Monitor Tool to perform the IFR spacing task (without autopilot).	4.4	.62
My awareness of ownship position was acceptable while I used the Range Monitor Tool to perform the IFR spacing task with autopilot coupled.	3.9	.99
It was easy to notice the decelerations of the TTF when using the Range Monitor Tool during the approaches flown without autopilot.	3.6	1.09
It was easy to notice the decelerations of the TTF when using the Basic CDTI.	3.4	1.09

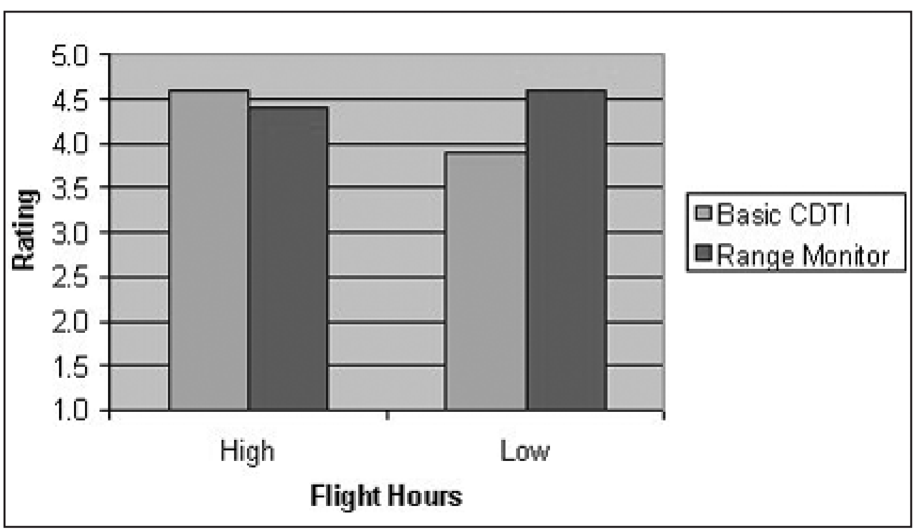

Figure 19. Effect of Equipment and Flight Hours on workload acceptability during VFR spacing.

high-hour pilots (2.8). High flight-hour pilots agreed more strongly (4.1) with an item stating they set and used the range ring than low flight-hour pilots (2.6), $F (1, 12) = 9.92$, $p = .0084$. Pilots using a CDTI showing other traffic agreed more strongly (3.9) with this statement than pilots using a CDTI that only showed the TTF (2.8), $F (1, 12) = 9.92$, $p = .038$.

As was found in the VFR data analysis, low and high hour pilot responses differed with regard to their use of certain CDTI features during IFR spacing. Low-hour pilots agreed significantly more strongly (4.9) than the high-hour pilots (4.3) that during the IFR spacing task they used the numerical range of the selected TTF, $F (1, 12) = 8.10$, $p = .015$. A significant interaction between Flight Hours and Traffic occurred in the responses to the statement that the pilot used the numerical closing rate (CR) when performing the IFR spacing task with the Range Monitor Tool, $F (1, 12) = 5.55$, $p = .036$ (Fig. 20). Tests for simple effects found a significant effect of Traffic for low-hour pilots, $F (1, 12) = 5.11$, $p = .043$ and a significant effect of Flight Hours for pilots who only had the traffic to follow on the CDTI, $F (1, 12) = 5.11$, $p = .043$. The former result indicates that the low-hour pilots who had other traffic on the CDTI agreed more strongly (4.6) than low-hour pilots who only had the TTF displayed (3.3) that they used the numerical closing rate (CR) feature. The latter result indicates that the high flight-hour pilots who only had the TTF on the display agreed more strongly (4.6) with the statement than those with low flight hours. Low-hour pilots disagreed significantly more strongly (2.2) than high-hour pilots (3.6) with the statement indicating that they set and used the range ring when performing the VFR spacing task with the Range Monitor Tool, $F (1, 12) = 5.22$, $p = .041$.

Yes-No Questions with Explanation and Additional Pilot Comments

This section includes a summary of pilot responses to questions that called for yes/no answers with explanation. Tabulation and transcription of these responses are in Appendix A.

Pilots were asked whether they made any errors in using the CDTI (any misinterpretations of displayed information, or anything you did incorrectly or omitted). Four of the 16 pilots responded on the VFR questionnaire and three of the 16 responded on the IFR questionnaire that they had committed errors. The errors differed among the pilots (see Appendix A for details).

A question on both the VFR and IFR questionnaires asked the Atlantic City pilots, "Was there a single, optimal CDTI range setting that enabled you (1) to perform the VFR/IFR spacing task while (2) remaining aware of nearby traffic?" Five responses ranging from 1.5 NM to 10 NM were obtained on the VFR questionnaire. The IFR questionnaire included four responses ranging from 1.0 to 5 NM. On both questionnaires, two pilots each provided two different "optimal" ranges.

Items were included to aid in the development of new procedures and further enhancements of the CDTI to safely perform spacing applications. In particular, the pilots were asked whether performing the VFR and IFR spacing tasks with loss of visual contact could safely accommodate certain situations. The items and results are found in Table 9.

The questionnaire included space for additional comments. The following is a summary of what the pilots wrote. See Appendix A for a complete transcription.

Neutral or Positive Comments: The majority of the comments about the spacing tasks and the features

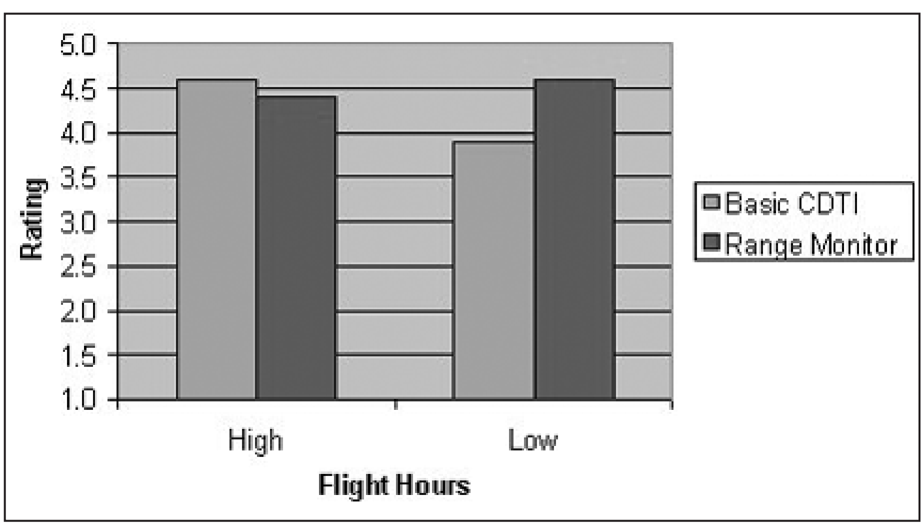

Figure 20. Effect of Flight Hours and Traffic on use of numerical closing rate while performing IFR spacing.

Table 7. Questionnaire Results for VFR Spacing Task Usability.

Statement	Mean	SD
I used the numerical range of the selected TTF when performing the VFR spacing task.	4.6	0.51
It was easy to find information on the Basic CDTI.	4.6	.51
The size of the CDTI display area was adequate for the information presented.	4.6	.51
It was easy to find information on the Range Monitor Tool.	4.5	.82
The VFR spacing task resulted in an acceptable amount of workload when I performed it using the Range Monitor Tool.	4.4	.63
I used the numerical closing rate (CR) when performing the VFR spacing task with the Range Monitor Tool.	4.2	.75
The VFR spacing task resulted in an acceptable amount of workload when I performed it using the Basic CDTI.	4.2	.83
I used the ground speed of the selected TTF when performing the VFR spacing task.	4.1	1.26
The track-up display showing a 360-degree view was more useful than the display showing the arc view for performing the VFR spacing task.	3.6	1.09
I used the Range Monitor Tool's "Target Range" feedback to help maintain the assigned spacing from the TTF while I performed the VFR spacing task.	3.5	.92
I set and used the range ring when performing the VFR spacing task with the Range Monitor Tool.	3.4	1.20
I used the closing rate arrow when performing the VFR spacing task with the Range Monitor Tool.	2.8	1.26
The spacing tools on the Range Monitor Tool added clutter without adding substantial benefit.	2.3	.93

Table 8. Questionnaire Results for IFR Spacing Task Usability.

Statement	Mean	SD
I used the numerical range of the selected TTF when performing the IFR spacing task.	4.6	.50
The size of the CDTI display area was adequate for the information presented.	4.6	.62
I used the ground speed of the selected TTF when performing the IFR spacing task.	4.4	1.20
It was easy to find information on the Range Monitor Tool.	4.4	.51
I used the numerical closing rate (CR) when performing the IFR spacing task with the Range Monitor Tool.	4.3	.86
It was easy to find information on the Basic CDTI.	4.3	.60
Adjusting the Range Monitor Tool display range during the IFR spacing task with autopilot coupled resulted in acceptable workload.	4.1	1.12
The track-up display showing a 360-degree view was more useful than the display showing the arc view for performing the IFR spacing task.	3.9	1.00
I used the Range Monitor Tool's "Target Range" feedback to help maintain the assigned spacing from the TTF while I performed the IFR spacing task.	3.9	.96
I was able to adjust the CDTI display range as often as I needed while performing the IFR spacing task (without autopilot) without experiencing excessive workload.	3.5	.74
I used the closing rate arrow when performing the IFR spacing task with the Range Monitor Tool.	3.0	1.10
I set and used the range ring when performing the IFR spacing task with the Range Monitor Tool.	2.9	1.36
The spacing tools on the Range Monitor Tool added clutter without adding substantial benefit.	2.4	1.03
The IFR spacing task caused excessive workload when I performed it using the Basic CDTI.	2.4	1.03
The IFR spacing task caused excessive workload when I performed it using the Range Monitor Tool (without autopilot).	2.3	.93
The IFR spacing task caused excessive workload when I performed it using the Range Monitor Tool (autopilot coupled).	1.8	.68

Table 9. Responses to Operational Concept Questions.

Can the VFR/IFR Spacing Task Safely Accommodate this Situation?	Yes	No
VFR		
ATC needs to insert a new VFR aircraft between ownship and the original spacing target aircraft.	16	0
You cannot re-establish visual contact after loss of contact (that is, due to landing into the sun, hazy conditions, etc.).	15	1
IFR		
ATC wants to allow an overtaking aircraft to assume your assigned spacing slot and to reposition (space) ownship with the assigned separation on the passing aircraft.	16	0
An upstream aircraft does not clear the runway expeditiously and your lead aircraft executes a missed approach.	16	0
During a runway change your target aircraft speeds up to expedite setting up the new approach path.	15	1

of the Range Monitor were positive. Three pilots commented that the system was beneficial for IFR procedures or in an IFR environment. Two described how the system improved situational awareness, collision avoidance, and safety. Comments regarding workload were somewhat mixed, but none described increased workload as an issue.

Negative Comments: Two comments were provided on the duplicate display of the CDTI ownship symbol and TIS-B symbol of ownship. The same pilot made these comments on the VFR and IFR questionnaires. Another display issue that a pilot mentioned is that it is difficult to detect the color change of a target symbol from cyan to green that occurs when a target is selected. These observations were later documented (see Appendix B). The duplicate symbol for N327DR is shown on the CDTI image in Appendix B, slightly to the right of the ownship symbol. Two pilots indicated the need to reduce the clutter and overlap from multiple airplane targets, and one suggested using a smaller size and a different symbol shape (e.g., an aircraft shape). The slow update rate of the target airplane altitude information was a concern for one subject. A pilot mentioned that the compelling display could reduce scanning out-the-window in VFR conditions. One pilot desired more practice and had issues with the safety pilot maintaining control of flaps and gear, which reportedly reduced performance.

SUMMARY OF RESULTS

An analysis of deviations from the assigned spacing indicated that VFR spacing using the Basic CDTI and Range Monitor was significantly more precise than spacing using Baseline equipment. The mean spacing deviation was .20 NM using the Basic CDTI and .18 NM using the Range Monitor. Baseline equipment provided a mean spacing deviation of .37 NM. IFR spacing using the Basic CDTI (.079 NM) did not differ significantly from IFR spacing using the Range Monitor (.083 NM) or Range Monitor with autopilot coupled (.093 NM).

Flight technical error was analyzed as horizontal deviations from the localizer and vertical deviations from the glide slope. No significant differences among the localizer deviations due to Equipment were found. The mean localizer deviations were .84 dots for the Baseline approaches, .67 dots for the Basic CDTI approaches, and .75 dots for the Range Monitor approaches. The mean glide slope deviation for Basic CDTI approaches (1.3 dots) was significantly larger than the mean glide slope deviations for Range Monitor (.98 dots) or Baseline (.85 dots) approaches.

Visual reacquisition times were measured on the downwind leg of the flight pattern and on final approach. No significant differences were found in the reacquisition times collected during the downwind leg. On final approach, the TTF was re-acquired more quickly when the pilot was using the Range Monitor (4.1 s) than no CDTI (18.2 s), but only for pilots using a CDTI that displayed TIS-B traffic.

Data from eye movement recording showed that 18% of the 27% attentional allocation to the CDTI during VFR spacing came from the forward window, and that 26% of the 30% allocation to the CDTI during IFR spacing came from the instrument panel. The CDTI received a 42% allocation during IFR approaches conducted with autopilot coupled. During VFR spacing, forward window dwell durations were longer during Baseline approaches (8.9 s) than during Basic CDTI (6.0 s) or Range Monitor (5.5 s) approaches. During IFR spacing, instrument panel dwells were longer during approaches conducted with Baseline equipment (17.1 s) than during approaches conducted with Basic CDTI (4.9 s), Range Monitor (5.3 s), or with Range Monitor/Autopilot (3.1 s).

Head-down time was analyzed as the time between fixations on the forward window during VFR spacing. Head-down time for approaches using Baseline (5.6 s), Basic CDTI (6.3 s), and Range Monitor (5.7 s) did not differ significantly. When the pilot used the Basic CDTI, head-down time was longer on approaches when the loss of visual contact overlapped the TTF deceleration (8.3 s) than when they occurred separately (4.3 s). Time between fixations on the CDTI and instrument panel were also analyzed. The mean CDTI "look away duration" for Basic CDTI approaches (13.4 s) did not differ significantly from the mean CDTI look away duration for Range Monitor approaches (11.6 s). The pilots with only the TTF shown on the CDTI looked away from the instrument panel for longer durations during Range Monitor approaches (24.9 s) than during Basic CDTI (15.5 s) or Baseline approaches (15.0 s). During the IFR approaches, the mean look away duration for CDTI was longer during the approaches with the Basic CDTI (11.0 s) and Range Monitor without autopilot (11.2 s) than during the approaches with Range Monitor and autopilot coupled (6.1 s). The mean look away duration for Panel was longer during the Range Monitor approaches with autopilot coupled (8.6 s) than during the Range Monitor approaches conducted without autopilot (4.4 s), the Basic CDTI approaches (4.4 s), or the Baseline approaches (2.8 s).

The NASA TLX workload scale addressed potential issues related to mental demand, temporal demand, effort, physical demand, own performance, and frustration. According to pilot ratings, use of the Basic CDTI for the IFR spacing task produced higher perceived mental and temporal demand than the use of Baseline equipment. Some evidence of higher mental demand for Basic CDTI, compared to the Baseline equipment, was also found in the VFR spacing task. On the other hand, the "own performance" workload dimension was rated higher (lower workload) when using the Basic CDTI or Range Monitor for VFR spacing, compared to Baseline equipment. The display of traffic, in addition to the TTF, imposed higher temporal demand and required more effort than the display of only the TTF during IFR spacing. Showing the additional traffic also led to lower ratings of own performance during VFR spacing. Examination of significant interactions between Equipment and Approach suggest that, whereas the use of Baseline or Basic CDTI equipment showed increases in effort and mental demand during the last of the four IFR approaches, the use of the Range Monitor showed a decrease during the last approach.

The VFR and IFR questionnaires addressed potential issues related to the pilot's ability to perform the spacing task and its possible effect on critical flight tasks. Pilots somewhat agreed that they could perform the VFR spacing task. They somewhat disagreed with the item indicating that the VFR spacing task interfered with their out-the-window and instrument scans. Low flight-hour pilots whose CDTI only showed the TTF agreed more strongly that they could perform the VFR spacing task than low-hour pilots whose CDTI also showed other traffic. Pilots whose CDTI only showed the TTF also agreed more strongly than pilots whose CDTI also showed other traffic that the CDTI aided visual reacquisition of the TTF after losing visual contact.

The pilots somewhat agreed that they could perform the IFR spacing task. They also somewhat disagreed with the item saying that the IFR spacing task interfered with their ability to fly a precise ILS approach or with their instrument scan during the IFR approaches. Pilots whose CDTI showed only the TTF agreed more strongly that they could perform IFR spacing than pilots whose CDTI also showed other traffic, and they also disagreed more strongly with the item that said the spacing task interfered with performing a precise ILS approach. High-hour pilots whose CDTI only showed the TTF disagreed more strongly than high-hour pilots whose CDTI also showed other traffic with the statement saying that the IFR spacing task interfered with their ability to fly a precise ILS approach. High-hour pilots disagreed more strongly with this item than low-hour pilots. On average, low-hour pilots neither agreed nor disagreed that the spacing task interfered with their ability to fly a precise ILS approach. High-hour pilots whose CDTI showed only the TTF disagreed more strongly with the item saying that the IFR spacing task interfered with their instrument scan than high-hour pilots whose CDTI also showed other traffic.

Situational awareness items on the questionnaires addressed potential issues with the accuracy with which the relative bearing of the TTF was displayed and the ease of noticing its decelerations. During VFR spacing, pilots using a CDTI that showed only the TTF strongly agreed that the relative bearing of the TTF was accurately displayed, whereas pilots using a CDTI that also showed other traffic only somewhat agreed. Pilots somewhat disagreed with the item saying that it was easy to notice decelerations of the TTF when using Baseline equipment, but they somewhat agreed that it was easy when using the Basic CDTI or Range Monitor. High flight-hour pilots using a CDTI that showed both the TTF and other traffic somewhat agreed that it was easy to notice the decelerations, whereas the low flight-hour pilots using this display neither agreed nor disagreed.

The usability items addressed potential issues with CDTI workload and the use of Range Monitor features. High-hour pilots strongly agreed that VFR spacing resulted in acceptable workload, whereas low flight-hour pilots somewhat agreed with this item. However, low flight-hour pilots using the Range Monitor agreed as strongly with the item as high flight-hour pilots using either Basic CDTI or Range Monitor. According to their responses, low flight-hour pilots benefited more from the Range Monitor tools than high flight-hour pilots when conducting VFR spacing. Low-hour pilots strongly agreed that they used the numerical range of the TTF during IFR spacing, whereas high flight-hour pilots somewhat agreed to this item. Low-hour pilots whose CDTI showed only the TTF agreed less strongly that they used the numerical closing rate feature than high-hour pilots and low-hour pilots whose CDTI showed other traffic.

Four VFR responses and three IFR responses indicated that the respondent had committed an error in using the CDTI. One VFR response said that the pilot misread altitude information, mistaking it for airspeed. One IFR response said that the pilot used the range ring interval as the (target?) distance when the range ring and text box overlapped. The questionnaires were not successful in eliciting "a single optimal CDTI range setting" for both spacing and traffic awareness: Responses ranged from 1.5 NM to 10 NM (VFR) and from 1.5 NM to 5 NM (IFR). Four responses each contained two ranges even though the item asked for one "optimal" range for both spacing and traffic awareness. Nearly all pilots stated that the spacing task could safely accommodate VFR situations in which ATC wants to insert a new VFR aircraft between ownship or the original spacing target and the pilot cannot re-establish visual contact following its loss. Nearly all agreed that the spacing task could safely accommodate IFR situations in which ATC wants to replace the original spacing target with an overtaking aircraft, the TTF executes a missed approach procedure, or the TTF speeds up to expedite setting up a new approach path. Most of the comments about the spacing tasks and Range Monitor features that were received in response to the open-ended "any additional comments" question were positive. They included statements that the system would benefit IFR procedures and improve situation awareness, collision avoidance, and safety. A pilot also commented on the double display of ownship, once as an ownship symbol and once as a TIS-B symbol. One pilot said that it was difficult to distinguish the cyan traffic from the green selected target. Two pilots were concerned about the clutter and overlap from multiple airplane targets, and one was concerned about the slow update rate of target altitude information.

DISCUSSION AND RECOMMENDATIONS

This study was conducted to provide the FAA Flight Standards Flight Technologies and Procedures Division (AFS-430) and the aviation industry with recommendations on human interface considerations for avionics that might be used to implement single-pilot general aviation procedures that utilize a CDTI for aircraft spacing. The first issue examined is whether pilots are able to maintain VFR spacing better using the CDTI than without a traffic display. Without the display, they could only guess at their actual distance, and the distance that they maintained is perhaps best regarded as the spacing that they achieve when ATC instructs them to maintain visual separation. With or without the traffic display, the pseudo controller instructed the pilot to maintain the current spacing interval. The Basic CDTI and Range Monitor both enabled pilots to produce reliably "better" (closer to assigned) spacing than the same pilots produced without a CDTI. The improvement was 0.17 to 0.19 NM. This result suggests that use of a traffic display could increase the regularity of the arrival flow to an airport compared to VFR spacing without a CDTI. This increase in regularity could occur with an increase in situational awareness and safety, as pilots reported that it was easier to notice the planned decelerations of the TTF when they were using a CDTI than when only scanning out-the-window. When using a CDTI, they also more quickly re-acquired the TTF following the loss of visual contact that the experimental procedures imposed.

Eye movement recordings indicated that pilots reduced their visual out-the-window and instrument panel scanning when using a CDTI to perform the VFR spacing task. On average, the length of individual out-the-window scans (or "dwell time") was shorter when the pilot used a CDTI. Perhaps pilots using a CDTI know where to look to more readily locate the traffic. However, a change in visual scanning for traffic that increases reliance on the traffic display should raise a caution flag because of the likelihood that not all traffic will always appear on the display. Although TIS-B traffic only requires an operating transponder for transmission to the CDTI aircraft, some aircraft have intermittent or inoperable transponders, requiring out-the-window scanning to see. Pilots "somewhat agreed" that they were "sufficiently aware of nearby traffic" while performing the VFR spacing task. The display of the additional traffic did not significantly affect these results, suggesting that traffic awareness continued to occur primarily through out-the-window scanning, or at least that the additional displayed traffic did not noticeably increase traffic awareness. Measured objectively, though,

pilots were found to look away from the traffic display for longer periods of time when it did not display the additional traffic, suggesting that when it was available, the additional traffic information was used.

One instance of possible over-reliance on the traffic display was recorded (see the in-flight experimenter's observations in Appendix C). The experimenter observed that, "The pilot was so focused on the CDTI that the aircraft flew uncomfortably close in trail of the target aircraft." Over-reliance on the CDTI, combined with misinterpreting target for ownship ground speed (observed with several pilots), may have caused the pilot to take the wrong action. This error appears to have occurred less when the pilot used the Range Monitor's numerical closing rate feature.

We investigated the possibility that CDTI use may itself represent an additional task with operational implications for the pilot due to increased workload. Evidence of a workload increase was found on approaches where the TTF decelerated separately from the loss of visual contact. Under these conditions, pilots perceived their mental demand as higher when using the Basic CDTI than when performing VFR spacing while not using a traffic display. On the other hand, they rated their own spacing task performance higher when they used the Basic CDTI or Range Monitor, compared to their perceived task performance without a CDTI. Thus, one workload dimension (mental demand) showed an increase, and another (own performance) showed a decrease in response to using a traffic display for VFR spacing. These mixed results do not apply to the VFR spacing task itself. They only indicate that using a traffic display for the task produced higher workload on the mental demand dimension and lower workload on the "own performance" dimension, compared to performing it without using a traffic display. The pilots either somewhat or strongly agreed that their workload was acceptable during the VFR spacing task, depending on whether they were using the Basic CDTI or Range Monitor, and on their flight hours. Low flight-hour pilots strongly agreed that workload was acceptable when using the Range Monitor, suggesting that the closing rate features may particularly benefit this pilot population. Low-hour pilots disagreed more strongly than high-hour pilots that the Range Monitor added clutter without adding substantial benefit, also supporting its advantages for this group. The only differences in feature use that were found, though, were that the high-hour pilots were more likely to adjust and use the range ring and less likely to use the numerical range of the TTF than the low-hour pilots. Significant differences between high and low-hour pilots were not found in their use of the closing rate features.

Some evidence gathered during this study suggests that the VFR spacing task may be better performed with only the TTF and without additional traffic displayed on the CDTI. The pilots rated their own performance higher (less workload) with only the TTF displayed, and low flight-hour pilots using displays with only the TTF strongly agreed that they could perform VFR spacing, whereas those with additional TIS-B traffic only somewhat agreed. Pilots using a TTF-only display strongly agreed that the traffic display aided their reacquisition of the TTF, but those with additional TIS-B traffic only somewhat agreed. Those using a TTF-only display strongly agreed that the bearing of the TTF relative to ownship was accurately displayed, whether flying straight ahead or turning, whereas those with additional TIS-B traffic only somewhat agreed. In contrast to these subjective results, use of a CDTI produced faster visual reacquisition times only when it displayed the additional traffic and the absence of additional traffic did not aid VFR spacing performance. That the pilots looked away from the traffic display for longer periods when it did not show the additional traffic also suggests that they found it useful when it was available. The key to understanding this discrepancy may be that it was difficult to use the traffic display for both general traffic awareness and VFR spacing at the same time. Half of the pilots said that they could not give a single optimal range for both tasks, and the others provided ranges that varied from 1.5 NM to 10 NM. Resolving this issue of simultaneously providing optimal traffic awareness and spacing task performance would require an examination of alternatives that was beyond the scope of this study.

The VFR and IFR spacing tasks differed in that the VFR task instructions were to maintain "at least" the assigned spacing interval, while the IFR task instructions were simply to maintain the assigned interval. IFR spacing performance did not result in any significant differences between the Basic CDTI, Range Monitor (without autopilot), and Range Monitor with autopilot approaches. In all of these conditions, pilots achieved a mean spacing deviation within 0.1 NM from what was assigned. The only significant differences in aircraft performance occurred in flight technical error where larger glide slope deviations were found on the Basic CDTI spacing approaches than on baseline approaches without spacing task performance, particularly when the TTF decelerated following the outer marker. This difference in flight technical error may be due to reductions in attention to other instruments when the pilot used a Basic CDTI. A smaller allocation of visual attention and shorter visual dwell time on the instrument panel were found during the CDTI approaches, compared to the

non-spacing approaches. However, the larger glide slope deviations may have simply been caused by the pilot's response to deceleration of the TTF as shown on the traffic display, a deceleration that did not occur during the baseline IFR approaches.

IFR spacing task performance with the Basic CDTI resulted in higher mental and temporal demand (time pressure) than flying an IFR approach without spacing (i.e., higher workload than on the IFR baseline approaches). However, the pilots somewhat disagreed with the statement that workload was excessive. When Range Monitor IFR spacing was performed with autopilot coupled, both mental and physical demands were lower than baseline workload.

The pilots whose traffic display only showed the TTF strongly agreed that they could perform the IFR spacing task, whereas those using a display that showed additional TIS-B traffic only somewhat agreed. High-hour pilots with no other traffic displayed disagreed more than high-hour pilots with the additional traffic that the task interfered with their instrument scan. Use of a traffic display that shows the additional traffic produced higher ratings on the Temporal Demand and Effort workload dimensions than displays that only showed the ownship and TTF. These workload results are consistent with the finding also seen in the VFR spacing task results that the pilots looked away from the traffic display for longer durations when it only showed the TTF than when it showed additional traffic. The additional traffic decreased perceived performance and noticeably increased pilot workload.

The IFR questionnaire results were examined to see whether high and low-hour pilots used different CDTI features. As was found in the VFR spacing results, low-hour pilots were more likely than high-hour pilots to use the numerical traffic range feature. Consistent with the hypothesis that low-hour pilots may use the advanced Range Monitor features to compensate for higher workload created by additional traffic, those who had the additional TIS-B traffic displayed strongly agreed that they used the Range Monitor's numerical closing rate feature, whereas those who only had the TTF displayed neither agreed nor disagreed with this item.

An issue that was not anticipated prior to conducting this study is that the display of traffic in addition to the TTF may hinder *perceived* spacing task performance and increase subjective workload. These results appeared in both VFR and IFR spacing task findings. Objective measurements found better visual-reacquisition of the TTF with the additional traffic displayed and no significant differences in spacing task performance or flight technical error. However, the additional traffic was associated with less time between fixations on the CDTI, supporting the subjective workload findings. A second issue that requires consideration is that the traffic display necessarily requires visual attention and reduces the attention available for scanning the instrument panel and on VFR approaches, the outside world. For this reason, even if pilots assume responsibility for spacing when they temporarily lose visual contact with the assigned TTF, they should notify ATC of the loss of visual contact so that controllers can assume responsibility for separation from other aircraft.

In summary, 16 multi-engine rated pilots were able to use a traffic display to conduct VFR and IFR approach spacing. During the VFR approaches, they were able to continue spacing using only the traffic display when the procedure imposed a temporary loss of visual contact with the TTF and to use the display to aid in re-acquiring the TTF. The Range Monitor numerical closing rate feature appears to particularly benefit the low-hour pilots because it can eliminate the workload required to compare own and TTF ground speed (as well as the potential for errors caused by mistaking one for the other). It is not clear whether these results would generalize to pilots who do not possess multi-engine ratings and/or to aircraft lacking a HSI/flight director. Before any procedures are developed that would include general aviation pilots, we recommend conducting a similar study with this population and platform. Finally, this study raises concerns regarding how traffic displays tend to capture the visual attention of pilots, to the detriment of out-the-window scanning for traffic. The danger of such attentional capture is that not all the traffic is necessarily represented on the display and therefore could come dangerously close to the aircraft before being noticed.

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APPENDIX A
Responses to Open-Ended Questionnaire Items

Did you make any errors in using the CDTI (any misinterpretations of displayed information, or anything you did incorrectly or omitted)?

VFR

4 of the 16 subjects reported making errors using the CDTI during the VFR task. The errors reported were different for each subject. 1st and 3rd bullets may not be errors.

- Not clear that closure rate is only displayed when tracks are within 40 degrees
- Error using target ground speed to help with distance
- First time was spent getting used to the indications.
- Sometimes misread altitude information mistaking it for airspeed

IFR

3 of 16 subjects reported making errors using the CDTI during the IFR task. The errors reported were different for each subject. Only first bullet may be an actual error.

- Range ring text block overlap. Used range ring interval as distance.
- Increased workload using ground speed and no autopilot
- Had to get used to closure indicator

Was there a single, optimal CDTI range setting that enabled you (1) to perform the VFR/IFR spacing task while (2) remaining aware of nearby traffic?

VFR

Four of the eight subjects with all traffic within range displayed on the CDTI responded “yes” and four responded “no”. Seven gave numerical responses. The following were provided:

- 1.5
- 5
- 10
- 1.5/5
- 4
- 5
- 2.0/5

IFR

Five of the eight subjects with all traffic within range displayed on the CDTI responded “yes” and three responded “no”. Six gave numerical responses. The following were provided:

- 1.5
- 1.0/5
- 4
- 5
- 3
- 2.0/5

Operational Concept Items (VFR)

In the VFR spacing task, the hood interval represents a time when you lose visual contact with the TTF. In your opinion, can the VFR spacing task with lose of visual contact safely accommodate these situations? If so, how? If not, what problem(s) would arise?

<u>ATC needs to insert a new VFR aircraft between ownship and the original spacing target aircraft.</u>

Yes	3
Yes with positive comments	6
Yes with strategy	1
Yes with reservations or qualifications	6
No	0

Reservations and qualifications include:

- With position reports to validate indications
- With proper experience and training
- After identifying it
- After getting used to the equipment
- May be difficult to acquire both visually
- Must still look out the window

<u>You cannot re-establish visual contact after loss of contact (that is, due to landing into the sun, hazy conditions, etc.).</u>

Yes	4
Yes with positive comments	7
Yes with strategy	0
Yes with reservations or qualifications	4
No	1

Reservations and qualifications include:

- With position reports to validate indications
- Pilot must fly the airplane and not fixate on the display

Operational Concept Items (IFR)

In your opinion, can the IFR spacing task safely accommodate these situations? If so, how? If not, what problem(s) would arise?

<u>ATC wants to allow an overtaking aircraft to assume your assigned spacing slot and to reposition (space) ownship with the assigned separation on the passing aircraft.</u>

Yes	4
Yes with positive comments	4
Yes with strategy	3
Yes with reservations or qualifications	5
No	0

Strategy:

- By setting the range ring to specified spacing and reducing speed to setup initial spacing

Reservations and qualifications:

- Wouldn’t want to rely solely on CDTI

- Some procedures should be established for overtaking airplane
- If on approach overtaking speed would get difficult
- Training should be required
- If not excessive workload or emergency
- If completed with enough distance before FAF

<u>An upstream aircraft does not clear the runway expeditiously and your lead aircraft executes a missed approach.</u>

Yes	7
Yes with positive comments	5
Yes with strategy	1
Yes with reservations or qualifications	2
No	1

Strategy:

- Now the spacing is between own and the runway aircraft giving it time to exit and your approach continues normally.

Reservations and qualifications:

- Realize they could no longer rely on the CDTI
- Would be an operational item.

<u>During a runway change your target aircraft speeds up to expedite setting up the new approach path.</u>

Yes	8
Yes with positive comments	4
Yes with strategy	0
Yes with reservations or qualifications	3
No	1*

* There was one “no” response with a comment. The subject responded “no” due to the loss of CDTI information when the target is more than 20 degrees left or right of the current track.

Reservations and qualifications:

- A/C configuration change
- As long as safety and stabilized approach can be met
- Might be difficult

Additional Comments

VFR Questionnaire:

1. The other pilot was using aggressive moves to change A/S without additional knowledge of Aztec performance. It makes the task more difficult. Also the right seat pilot was in control of the flaps & gear, if I had that control, performance would definitely increase. A longer time to familiarize with the traffic avoidance before testing would be helpful. (Atlantic City Subject)
2. Targets altitude information is slow to update e.g. 2 seconds to display correct indication. I observed this as I was climbing and target has already leveled off. (Sanford Subject)
3. Please remove the ownship TIS-B target from the display. There needs to be another way to remove the clutter from the screen, perhaps targets could be smaller until they are not a factor. Make the target a better shape, perhaps an airplane shape. (Atlantic City Subject)
4. I could maintain proper range with loss of visual of target. That could however preclude pilots from looking outside in VFR conditions. (Atlantic City Subject)

5. The range monitor tool was much more helpful than basic CDTI in the VFR spacing exercise in not interrupting instrument scan. Ground speed placement of my a/c and target a/c read more easily and closing rate info very useful in power changes. (Atlantic City Subject)
6. Everything worked fine and I don't see any problems as long as no unforeseen things occur, i.e. added traffic, emergencies, etc. (Atlantic City Subject)
7. I feel the system greatly increases safety. It would decrease controller workload and allow for more aircraft to safely use airspace. Uncontrolled non-RADAR airspace would have a great improvement in safety and lower accident rates of mid-air collisions. (Sanford Subject)
8. The CDTI adds timely and effective situational awareness during high workloads when entering airport traffic patterns. I found the CDTI was very effective in showing all other traffic in my area, as well as allowing the pilot to predict the future position of other traffic. This trend information makes it much easier for the pilot to employ collision avoidance action plans. I also found that the time to interpret the CDTI was very short and effective. Occasional glances at the display allowed for a great benefit when looking out the window visually. I could use my peripheral vision on the CDTI while focusing on the outside window picture. (Sanford Subject)

IFR Questionnaire:

1. The duplicity of the two icons for one aircraft needs to be taken care of. The target selection color change: blue and green are too close to each other. Something needs to be done about information overlapping on the display. (Atlantic City Subject)
2. Approaches without autopilot may be difficult for pilots who do not fly on a regular basis. (Atlantic City Subject)
3. Using closure rate information is much more helpful than only using ground speed information. (Atlantic City Subject)
4. It seemed easier to fly while IFR only. (Atlantic City Subject)
5. The IFR portion of this test was easier due to the aircraft to follow was on a published approach segment. Although this is the time the CDTI proved to be an asset in situational awareness and aircraft planning. (Sanford subject)
6. I don't think this system caused excessive workload. If you know where to look for information you want from the MFD, you just need to incorporate it into your scan. Obviously, there is additional workload, especially without the autopilot but I believe it is manageable. Over all I think it is a great tool. (Sanford subject)
7. The system would allow closer spacing during IMC IFR operations at a busy airport. It would also allow better operations at uncontrolled airports as well as non-RADAR airspace. (Sanford subject)

APPENDIX B

Documentation of Traffic Display Issues From Pilot Comments

The photograph below depicts two issues brought forth in pilot comments: a duplicate TIS-B symbol for ownship (N327DR) and difficulty discriminating cyan aircraft targets from the green selected aircraft target.

APPENDIX C

In-Flight Experimenter's Observations and Recommendations

VFR Approach Spacing

There were no surprises in the data showing that pilots were much better at maintaining an ATC-assigned spacing during VFR operations when given a CDTI that provides distance/ ground speed of a selected target. The comparison or "baseline condition" in this case was the pilot's eyes, and they could not be expected to accurately judge distances accurately solely from "out-the-window" information. The subject pilots flew this baseline for workload comparisons and, without question, having a CDTI made the pilots more comfortable. They used the CDTI to help plan their base and final turns, even when they had lost sight of the target aircraft. However, we did have one situation where the pilot was so focused on the CDTI that the aircraft flew uncomfortably close in trail of the target aircraft. It was not clear whether the primary reason was the subject's misinterpretation of the CDTI information or if it was lack of experience in the aircraft. While this only happened on one of the 64 VFR approaches flown, it does show that the compelling nature of the CDTI, when used in a tactical manner, might cause a pilot to fixate on the task and/or display.

During Basic CDTI operations, pilots were required to look in two different places for groundspeed. The target's groundspeed was on the multifunction display, and the subject's groundspeed was on the GPS navigator located directly below the multifunction display. We observed several pilots making the mistake of using the target's ground speed as their own and vice versa, which resulted in the wrong choice of action. These mistakes didn't occur as often using the Range-Monitor CDTI when closing rate information was given. It should also be noted that it was very helpful having all the required information located in close proximity on the Range Monitor display. The Range-Monitor provided all the information the pilot needed to maintain spacing next to the target symbol, and in addition provided both ownship and target groundspeed on the same multifunction display.

The results of the VFR portion of the study indicate to us that with training, general aviation pilots could use a CDTI similar to the Range Monitor prototype we used in this study to "help" ATC provide safe arrival spacing in visual conditions.

IFR Approach Spacing

We expected to see a larger difference in flight technical error between the baseline IFR approaches and those requiring the subject to maintain a specific spacing. However, without exception, each subject was able to accurately fly an ILS approach and safely maintain an ATC assigned interval. In no case did we consider an approach "unsafe," nor was a missed approach required due to tracking errors on either the localizer or glide slope.

It should be noted that all our subjects were at least current commercial/instrument multiengine rated pilots. Many were instructors and several were career FAA flight check pilots. In addition, the aircraft was equipped with a horizontal situation indicator that makes flying an ILS much easier. The results would most likely have been different with low-time, instrument-rated private pilots in an aircraft with basic IFR capabilities. Before any procedures are developed that would include general aviation pilots, we recommend the completion of a similar study with this population and platform.

While our subjects were able to fly an ILS and maintain an assigned spacing, we think it would benefit the pilot to have the spacing information in the same field of view as the ILS display. For example, the Sandel Electronic HSI that displays localizer/glide slope, as well as mapping data, could easily accommodate a target spacing field. It would also be beneficial to be able to provide

selected target information on the standard map screen on the multifunction display, as opposed to requiring selection of a specific traffic display. Currently, no mapping information other than the active flight plan can be displayed on the traffic screen, and the standard map screen will display the traffic, but it is not selectable. The prototype Range Monitor display also provided a pilot-configurable range ring to provide a visual cue about distance from the target. The implementation of this was rather clumsy and difficult to adjust quickly. However, we feel that a better implementation may provide a useful reminder of the spacing requirement.

The results of the IFR portion of the study indicate to us that with training and equipment similar to the CDTI we used in this study, it is feasible that general aviation pilots could participate in approach spacing operations in IFR conditions. However, additional research is needed to determine the minimum training and experience that should be required and whether or not an aircraft requires a Horizontal Situation Indicator/Flight Director and/or autopilot for its pilot to conduct approach spacing.